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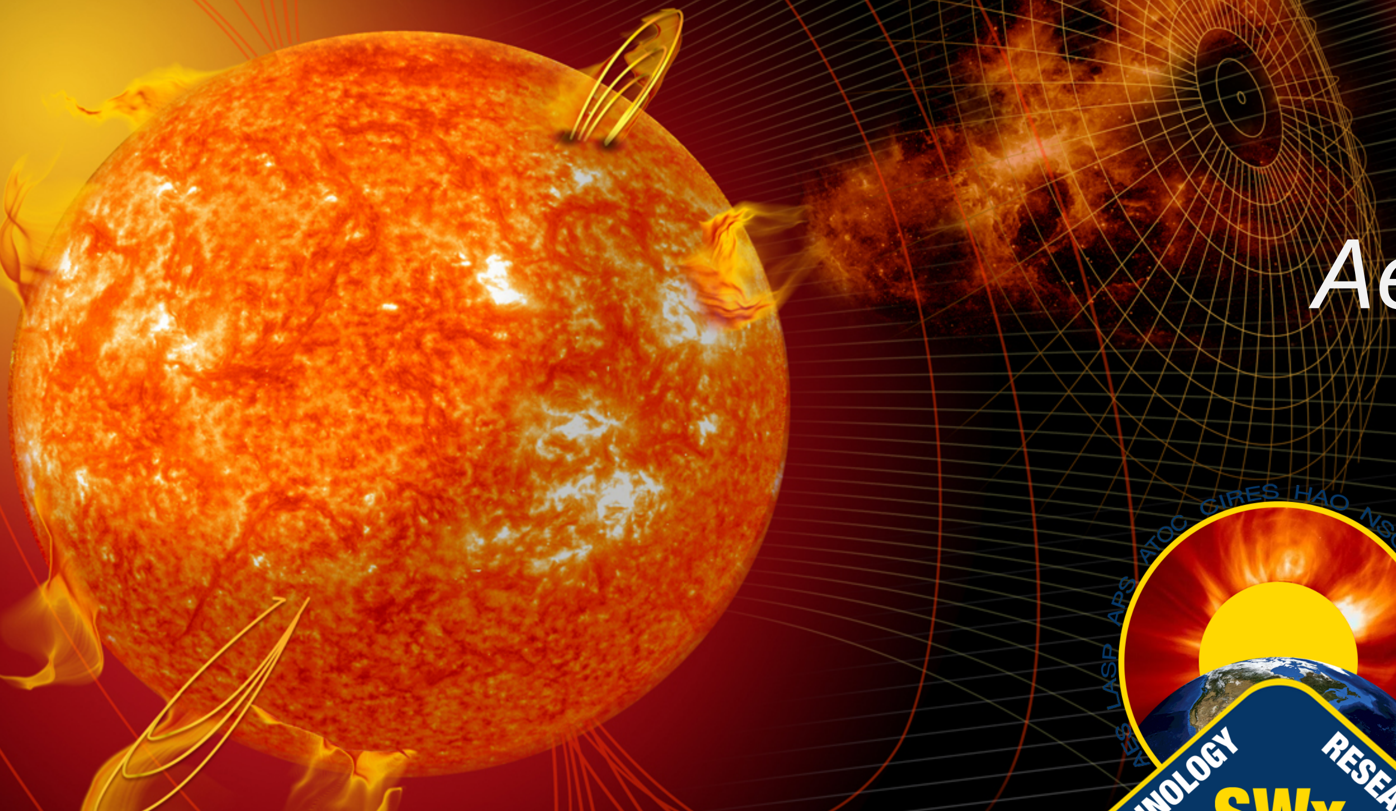

Satellite Drag: Aerodynamic Forces in LEO

Marcin Pilinski

SWx-TREC

LASP / University of Colorado

2018-04-25

9th CCMC Community Workshop

College Park, Maryland

Laboratory for Atmospheric and Space Physics

University of Colorado **Boulder**

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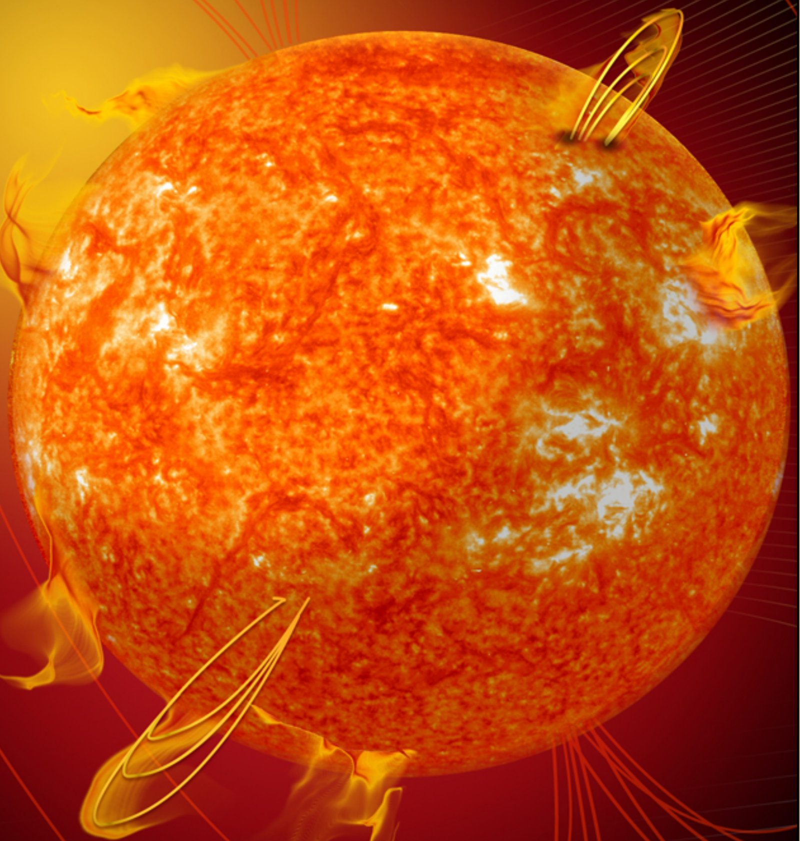

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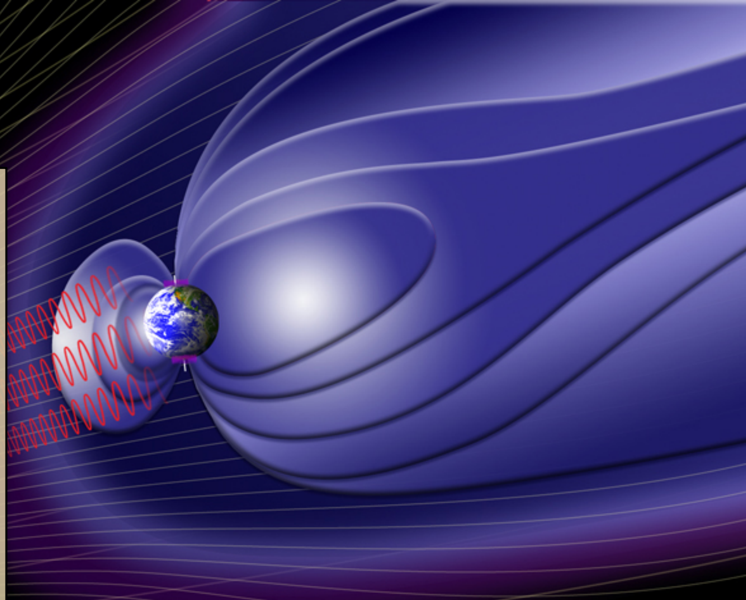

Jeffrey P. Thayer, PI (AES), Tom Berger, Director (CEAS), Dan Baker (LASP), Steven Cranmer (APS), Chris Pankratz (LASP), Tim Fuller-Rowell (CIRES), Nils Halverson (APS), and Cora Randall (ATOC)

TREC is a new academic initiative to serve as a national center of excellence in cross-disciplinary research, technological innovation and education in space weather. As an academic endeavor, SWx TREC provides new pathways for federal agencies, academia, commercial partners and industry to collaboratively address the nation's evolving space weather forecasting, mitigation and response needs.

AES LASP APS ATOC CIRES HAO NSO SET ASTRA SWRI

TECHNOLOGY SWx RESEARCH

EDUCATION

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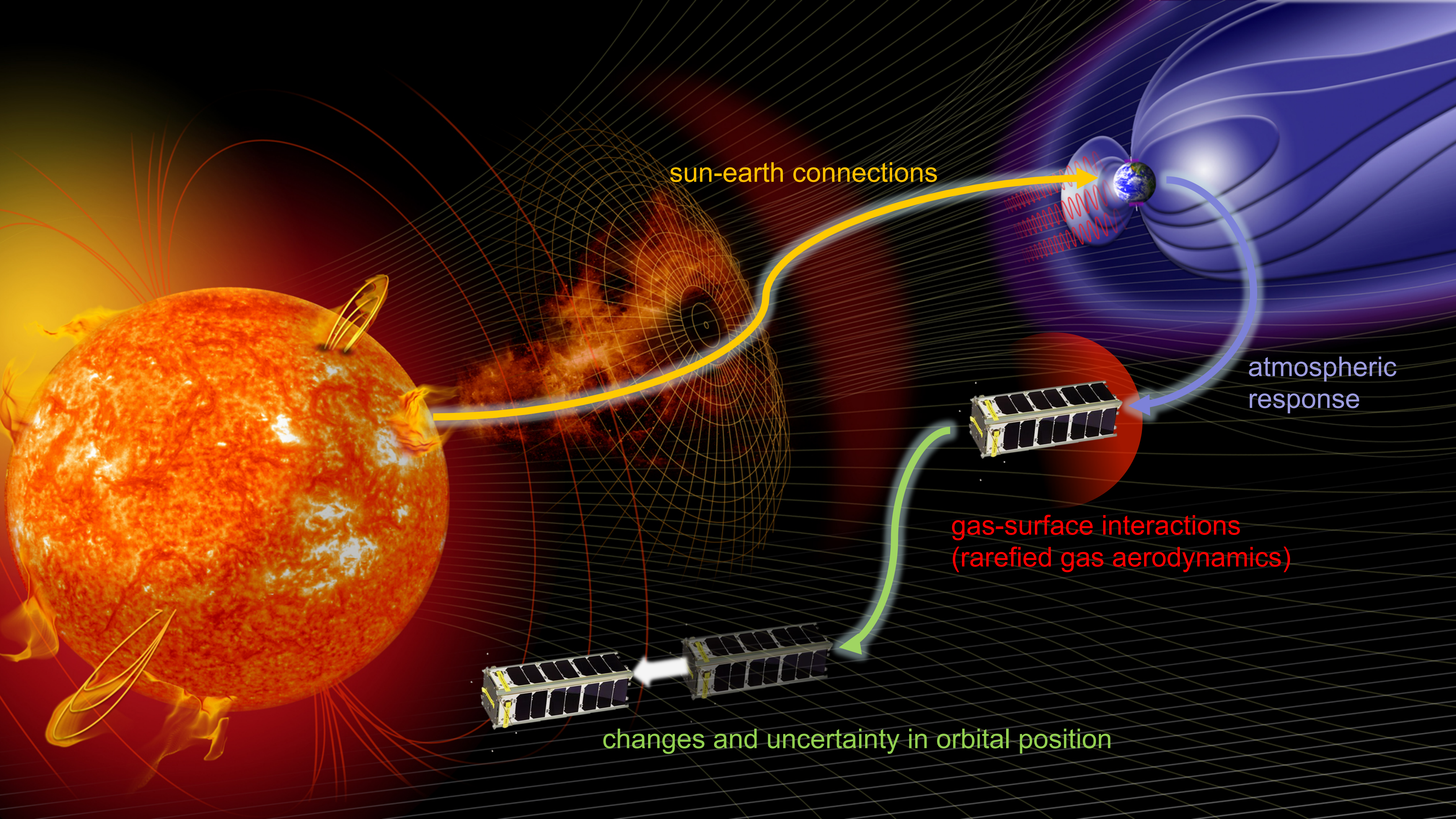
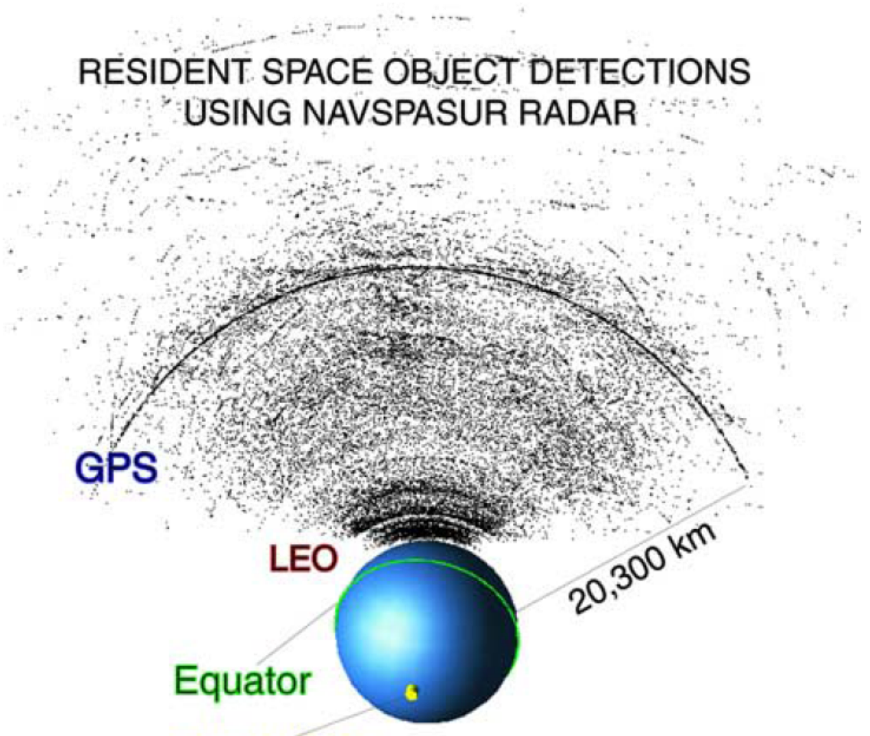
SWx-TREC

Satellite drag is one of our focus areas

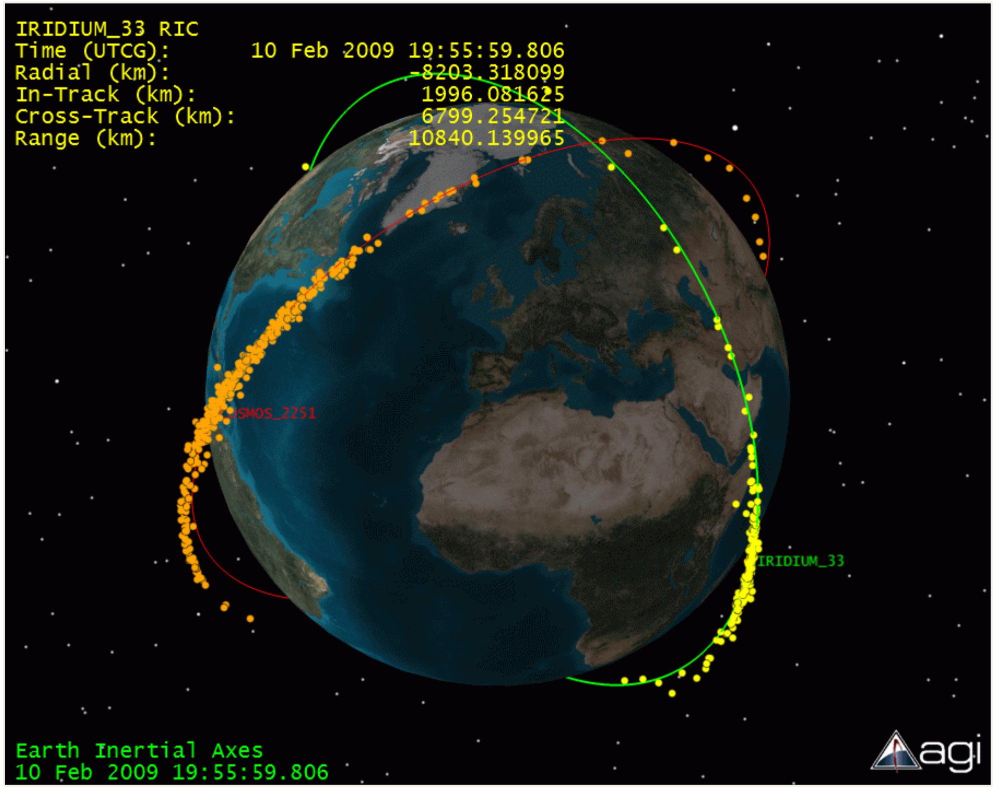
- Interdisciplinary (Astrodynamics, Solar Physics, Aeronomy, Gas-Surface Physics, Modeling and Computation)
- ”Problem of the Commons”
- Opportunities for O2R and R2O transitions


sun-earth connections
atmospheric
response
gas-surface interactions
(rarefied gas aerodynamics)
changes and uncertainty in orbital position

Resident Space Objects and the LEO Environment



from Picone et al. 2005



Satellite drag errors degrade capability to:

- Maintain accurate catalog of all space objects including debris
- Predict and avoid space collisions
- Predict satellite reentry time & location
- This is not small satellite problem vs. big satellite problem, it is an issue for all space assets

In 2016…

Total Number of CubeSats Launched 417	Total Number of Debris Generated by DMSP Satellites 346
Total Number of Debris Generated by Cosmos-Iridium 1296	Total Number of Debris Generated by Fengyun ASAT 3428

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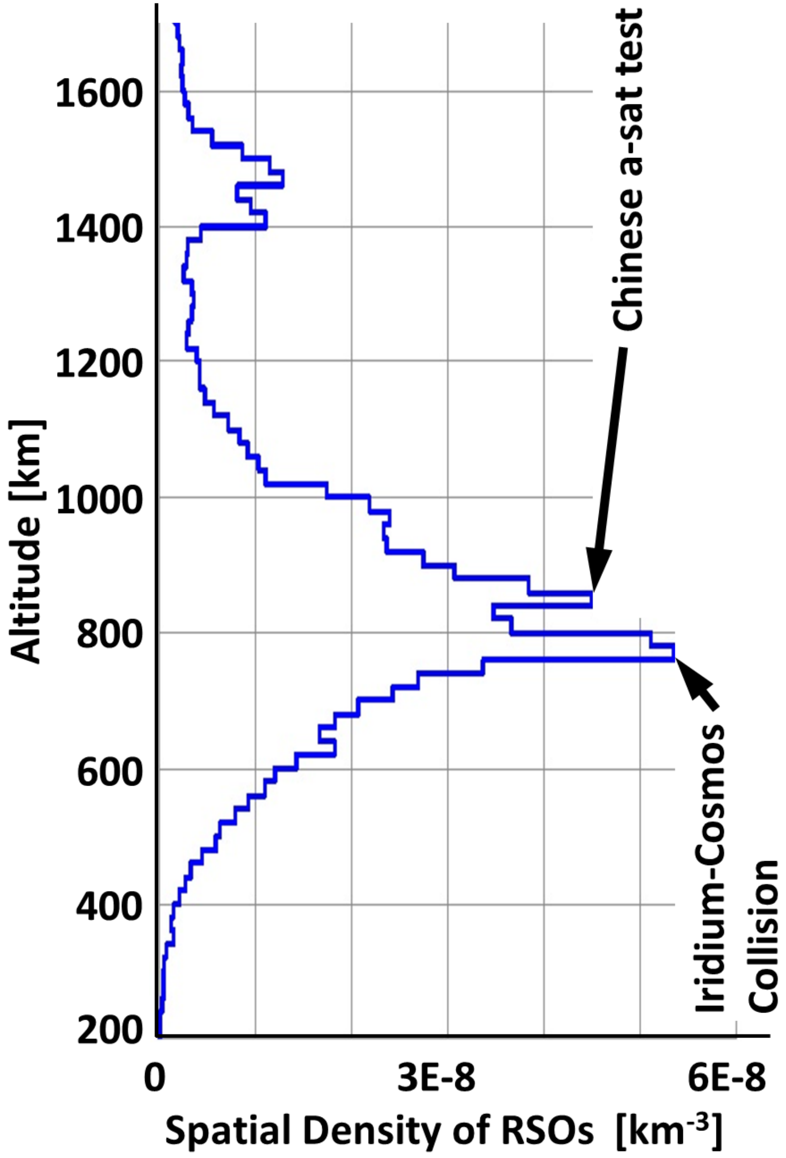
Resident Space Objects and the LEO Environment



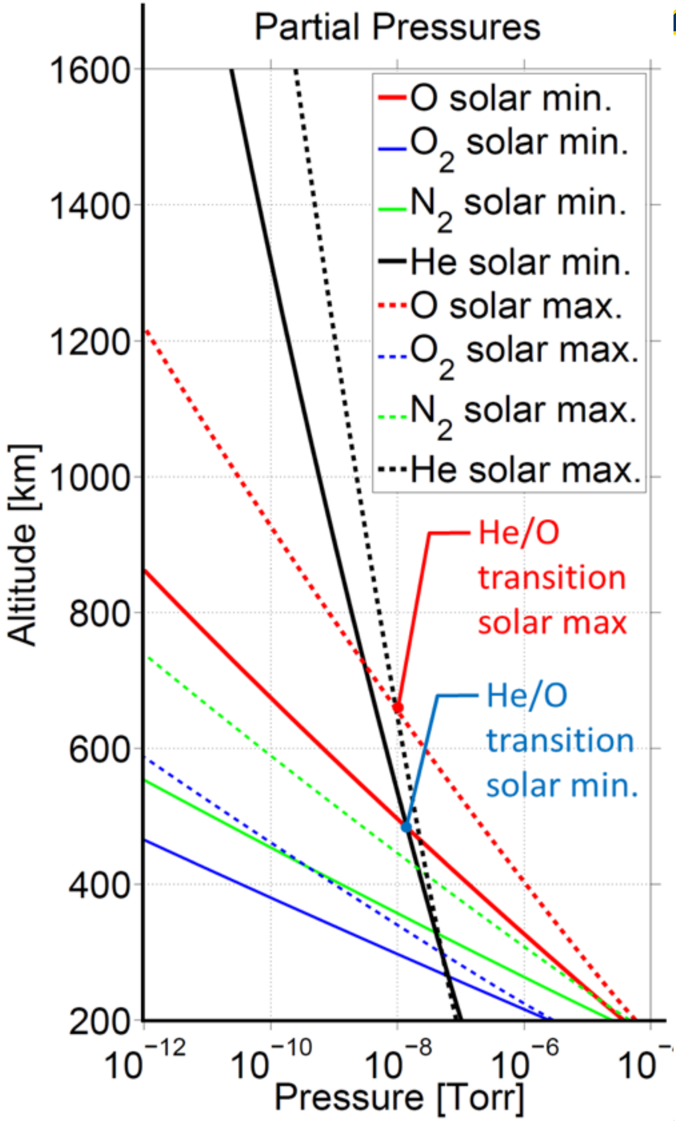
While SRP[1] is larger in magnitude, aerodynamic drag is the most variable force and the primary contribution to orbit errors

Drag is the dominant non-conservative force

free-molecular flow

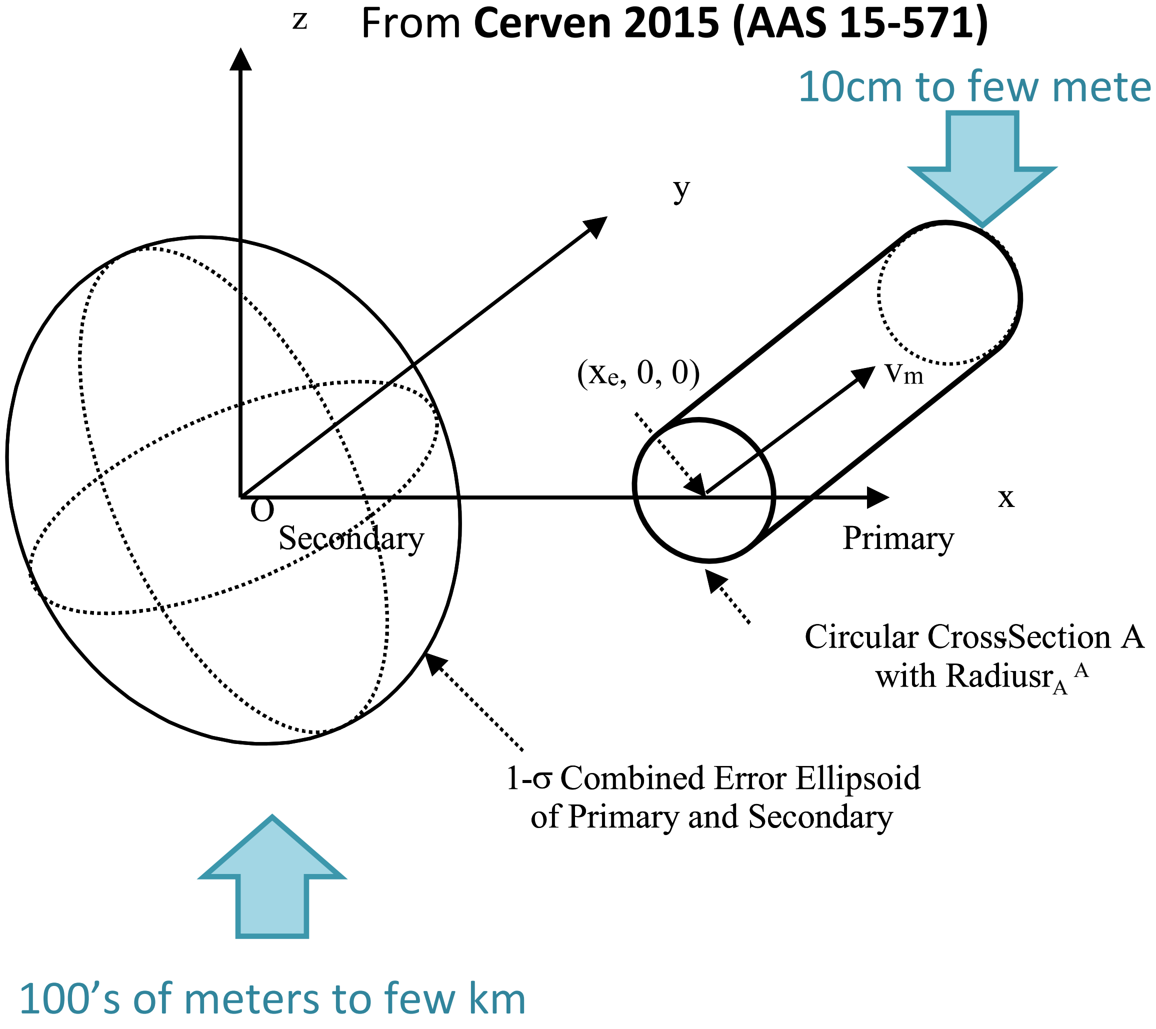
composition and temp. drives gradual changes in C_D

re-entry, extreme C_D variability



Predicting Collisions: Conjunction Analysis

From **Cerven 2015 (AAS 15-571)**



$$Pc = \iiint_V \frac{1}{\sqrt{(2\pi)^3 |C|}} e^{-\frac{1}{2}\mathbf{r}^T C^{-1} \mathbf{r}} \, dx \, dy \, dz$$

- Collision Probabilities (P_c) determine the threshold for operational action
- General Assumptions
  - Two spheres
  - Gaussian probability distributions
- P_c is the "integral of the combined positional **error distribution** (C) within the tube swept out by the relative motion of the primary with respect to the secondary (v_m) given a combined hard body radius (r_a)" (Cerven 2015)

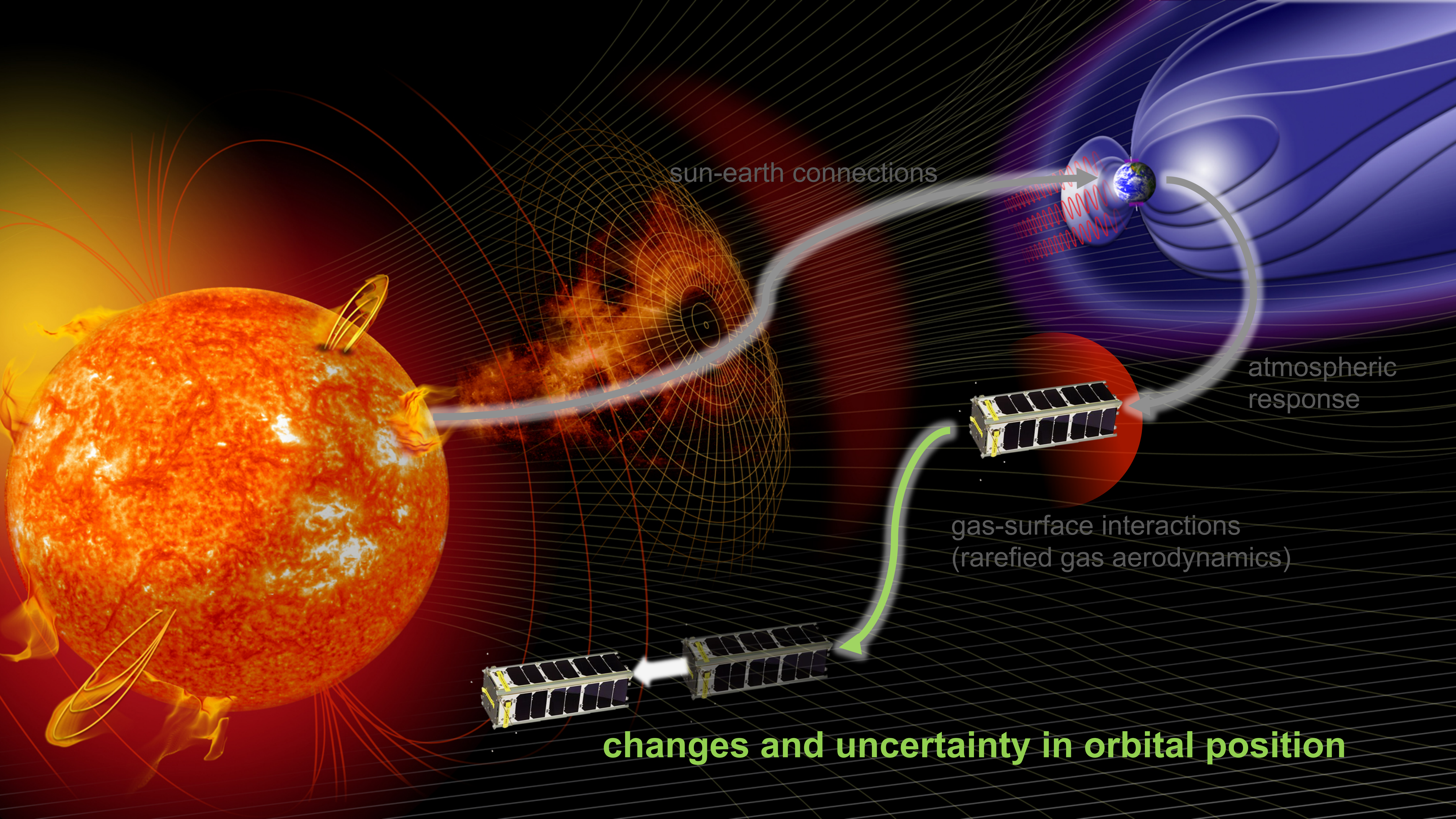
Conjunction Analysis

- Satellite Drag has a significant impact on P_c of LEO objects
  - Combined positional error distribution
  - Estimate of relative positions

- With the growing numbers of RSO's, number of warnings based on Pc is starting to be "not actionable"
  - over 18,000 conjunctions within 5 km for the coming 7 days
  - ~800 per day for NASA satellites alone

Other Satellite Drag Impacts

- Re-Entry Predictions
  - Involves lower atmosphere dynamics
  - Flight dynamics in the lower Thermosphere and Mesosphere
  - Transition from free molecular flow to rarefied gas dynamics
- Mission Lifetime Estimates
  - Long term estimates of solar activity and atmospheric response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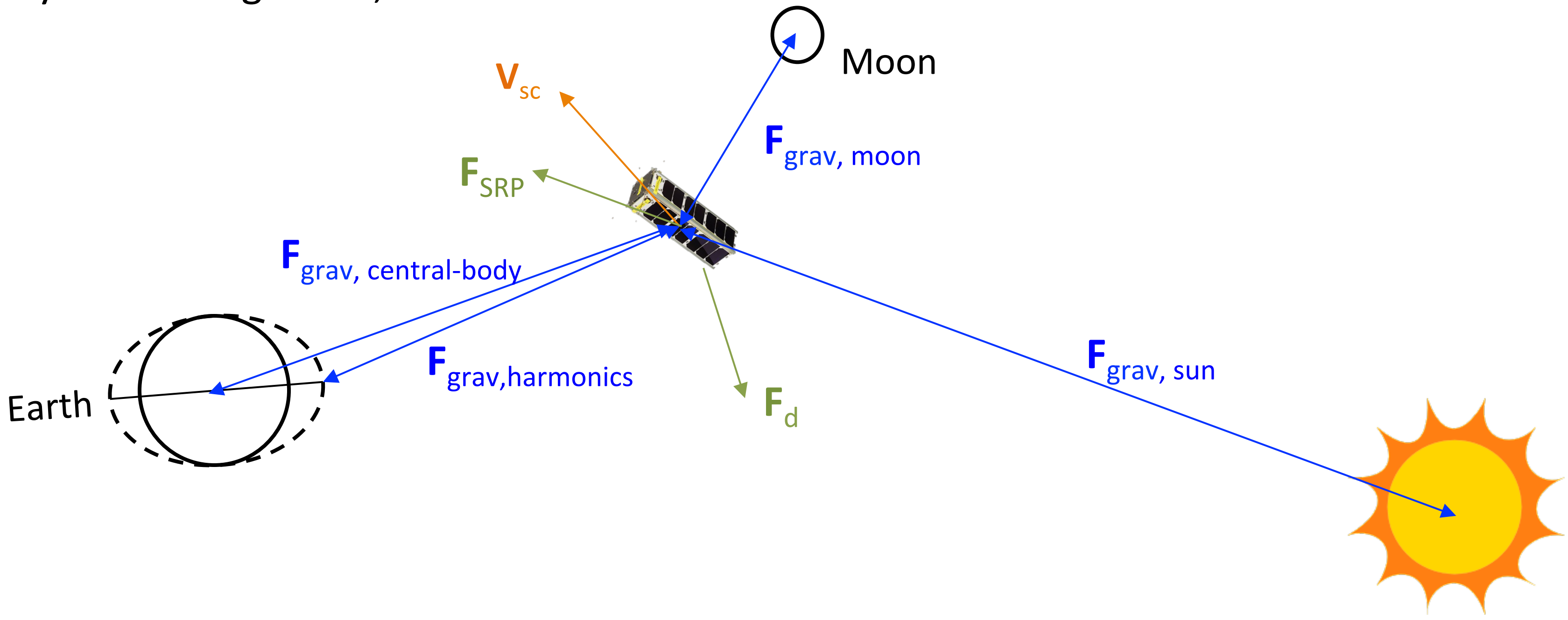
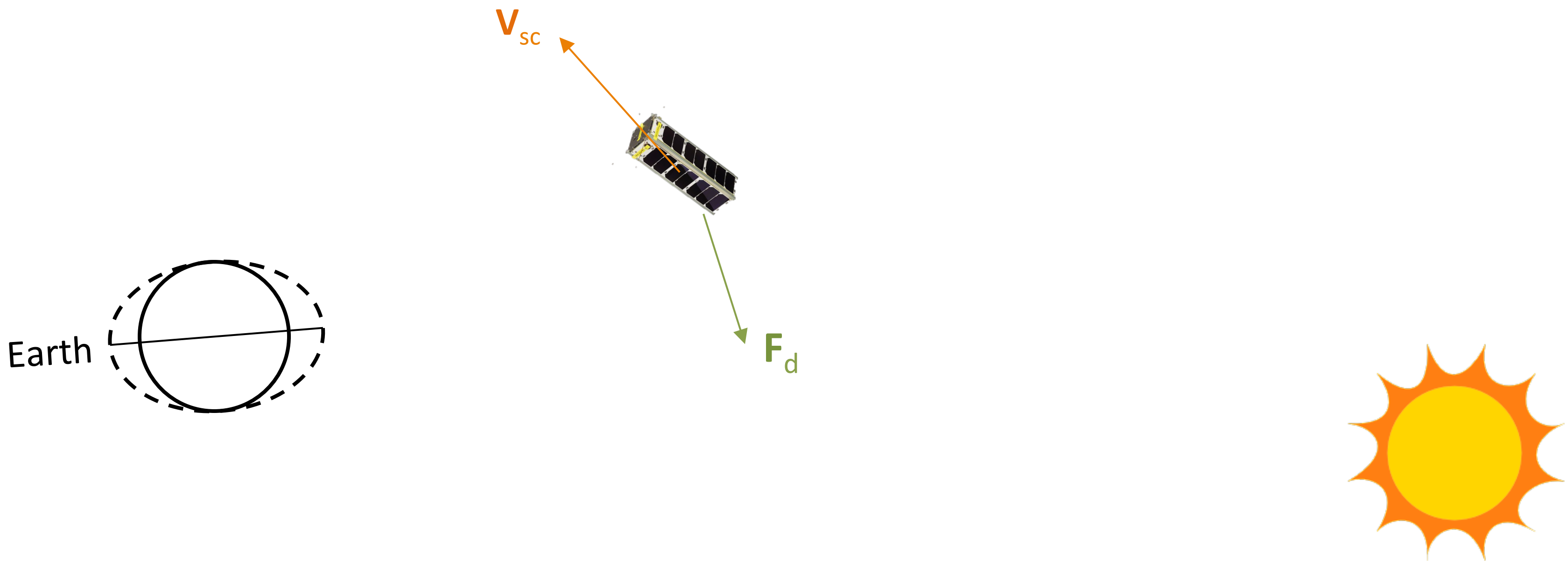
Orbital Perturbations

V_{sc} Spacecraft Velocity
F_{grav} Gravitational Forces
F_{SRP} Solar Radiation Pressure, Surface Force
F_{d} Aerodynamic Drag Force, Surface Force

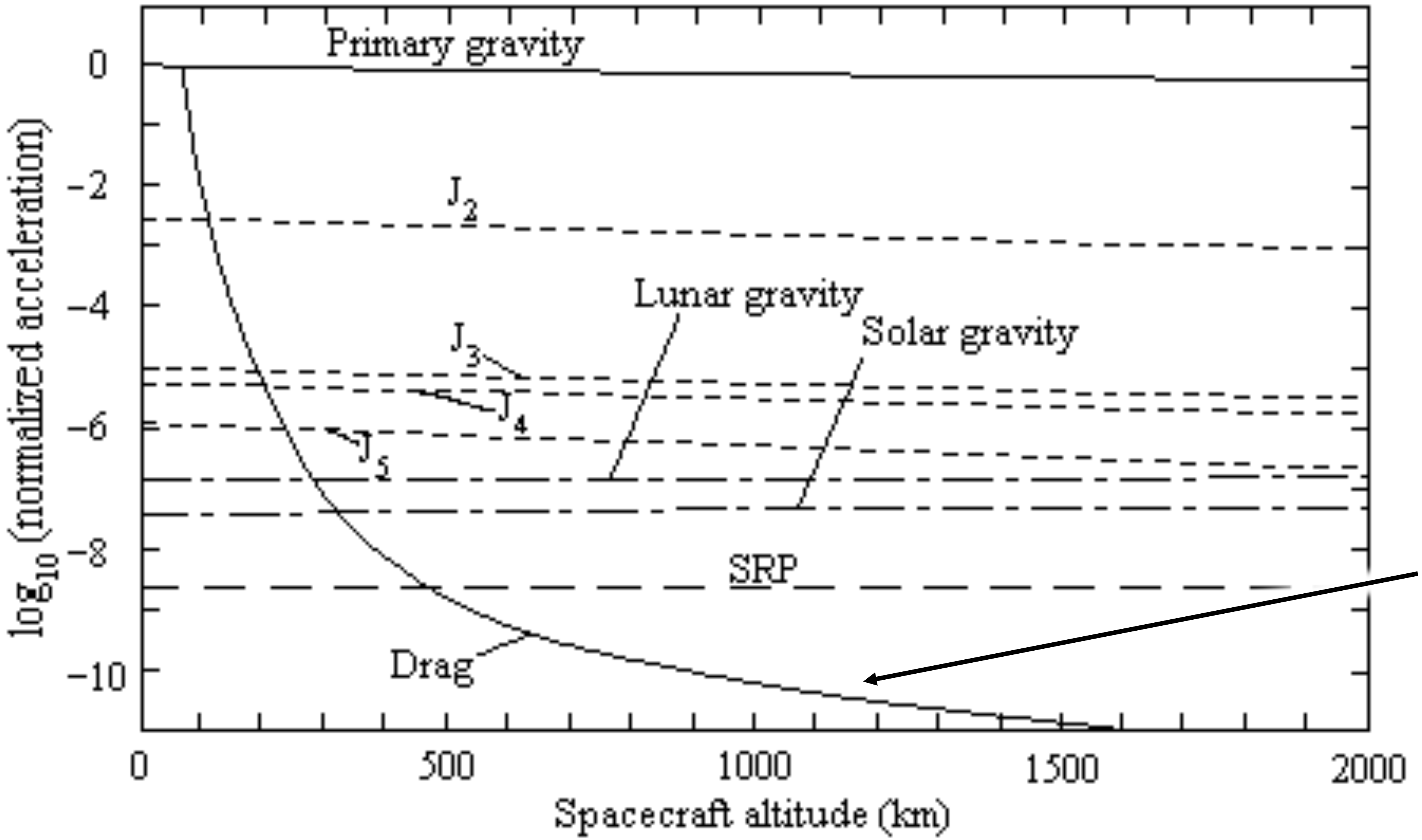


Surface Forces

V_{sc} Spacecraft Velocity
F_{grav} Gravitational Forces
F_{SRP} Solar Radiation Pressure, Surface Force
F_d Aerodynamic Drag Force, Surface Force



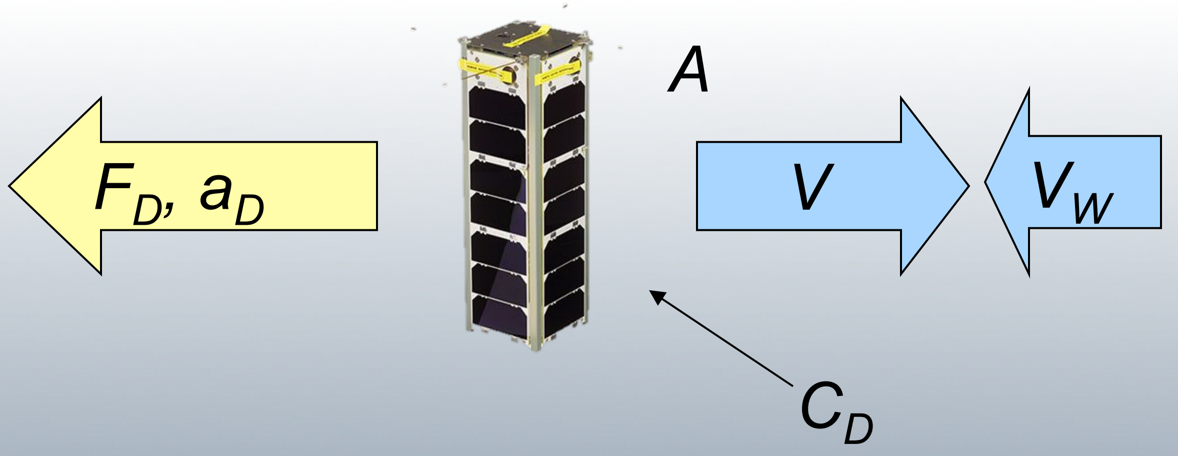
Orbital Perturbations



Most variable and uncertain of any of the other perturbations

Astrodynamics of Satellite Drag

$$\mathbf{a}_D = -\frac{1}{2}\,\rho\,\frac{C_D\,A}{m}\,V_{rel}^2\,\hat{\mathbf{V}}_{rel}$$



atmosphere

ρ – density

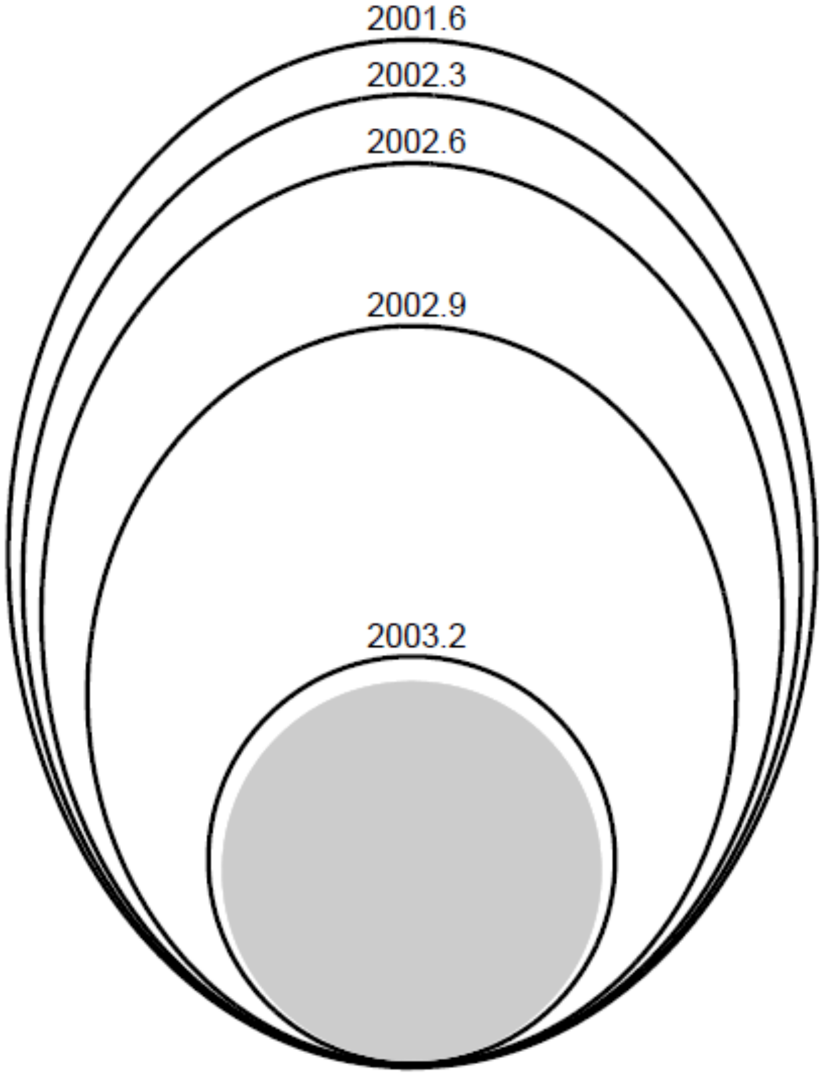
T_a – temperature

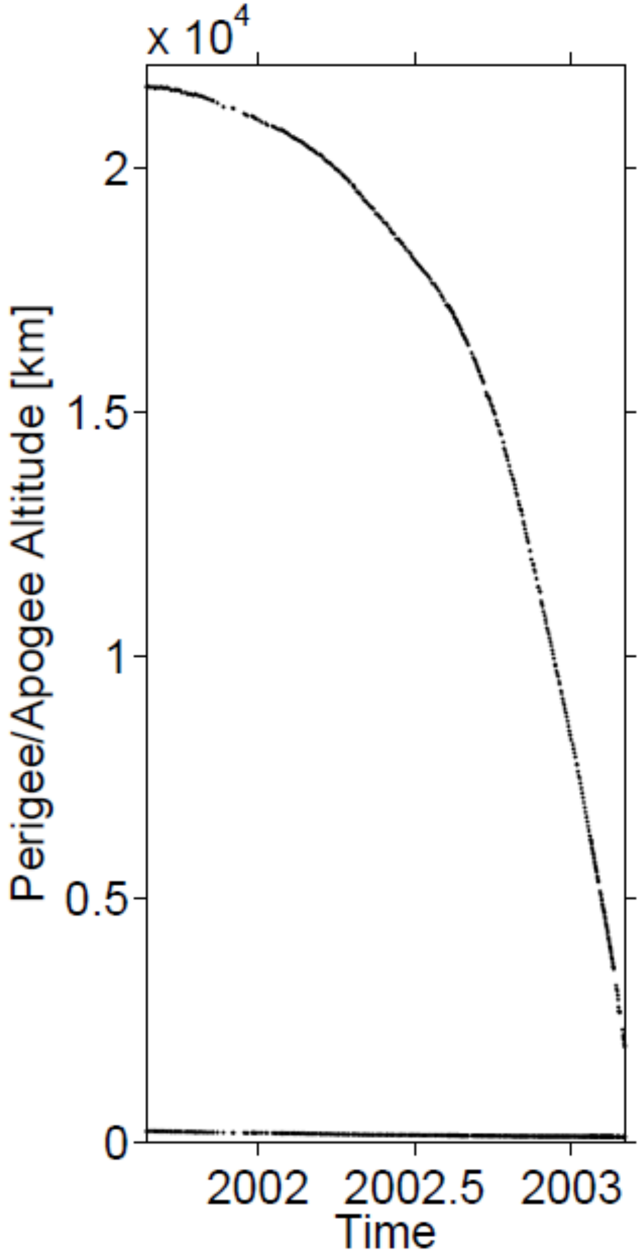
composition

F_D drag force
A cross sectional area
C_D drag coefficient
V spacecraft velocity
V_w atmospheric winds

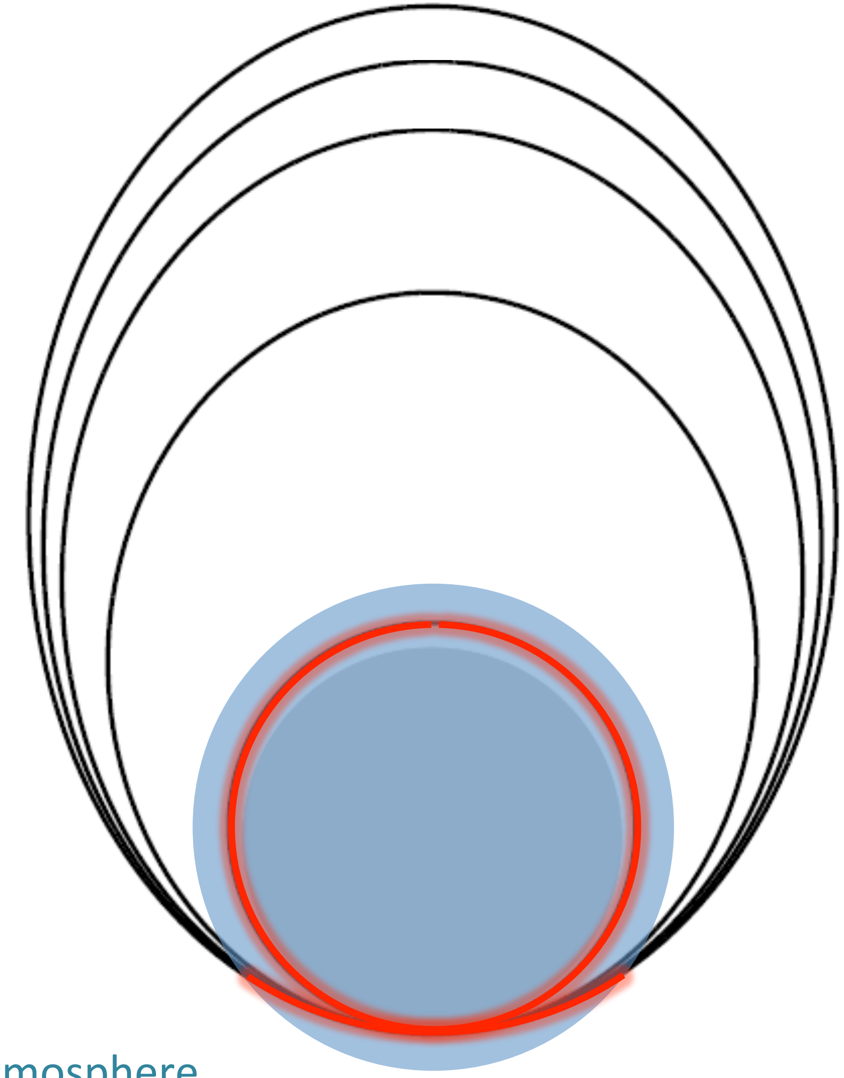
$\mathbf{V}_{rel}$ vector sum of **V** and $\mathbf{V}_w$

An Illustration of Orbital Decay





Energy Dissipation Rate (EDR)



atmosphere

orbital energy dissipation

Work done by aerodynamic drag along the orbital path l

$$B/2\, \rho \|V_r\|^2\, l$$

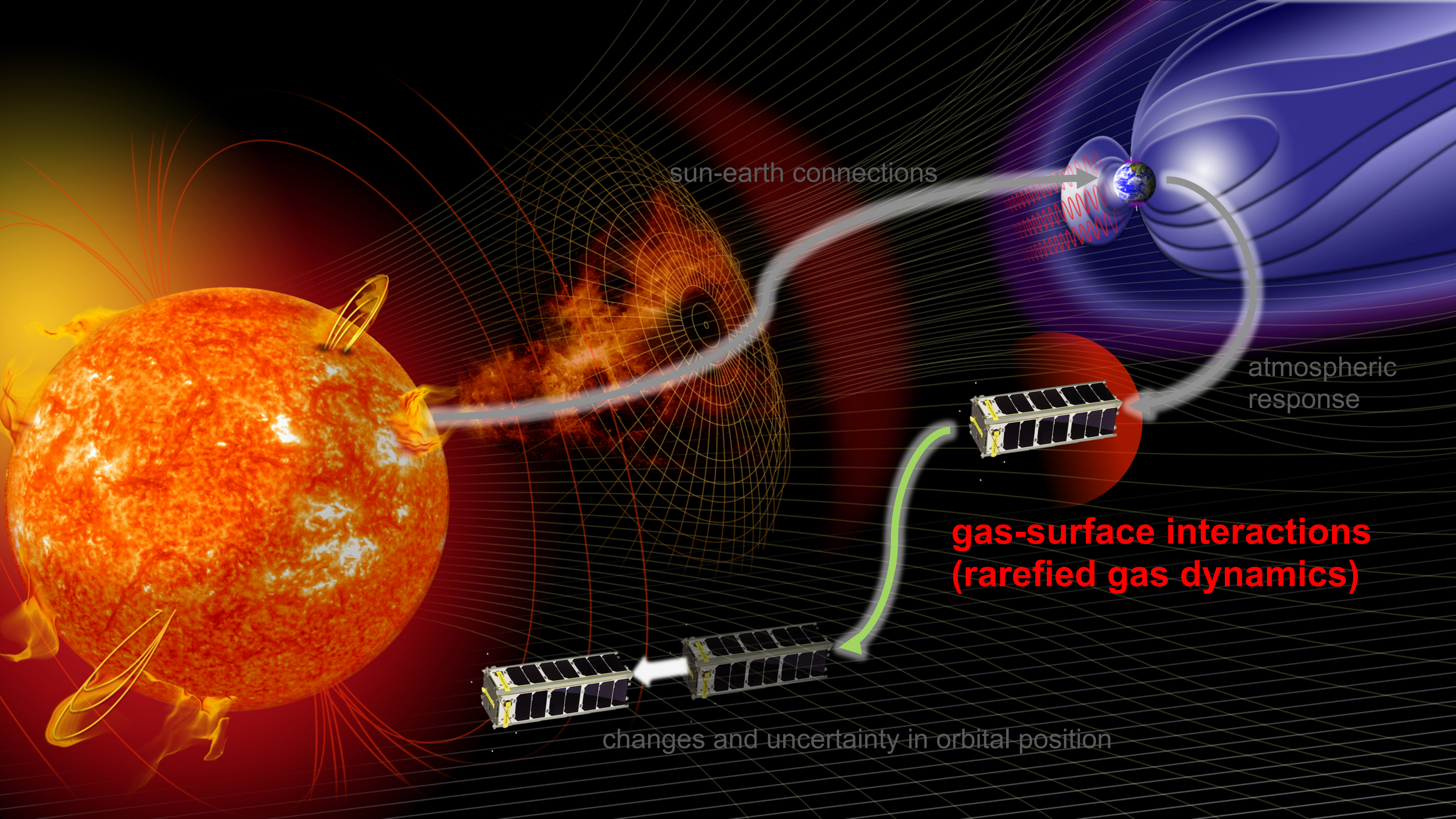
Rewriting as a line integral, separating the "constant" terms, and dividing by a time interval results in the EDR

$$\varepsilon = 1/2\Delta t \int_{t_i}^{t_k} B\rho \|V_r\| (V_r \cdot V_{sat})\, dt$$

Assuming there are no significant in-track SRP effect nor 3rd body effects or that these can be removed, we can relate the EDR to change in mean-mean motion

$$\dot{\varepsilon}_{\text{obs}}\left(t_{ik}\right) = \frac{\Delta n}{3 n_A \mu^{-2/3} \Delta t}$$

Mean motion, n, determines where the satellite will be along its orbit at any given time (in track motion)


sun-earth connections
atmospheric
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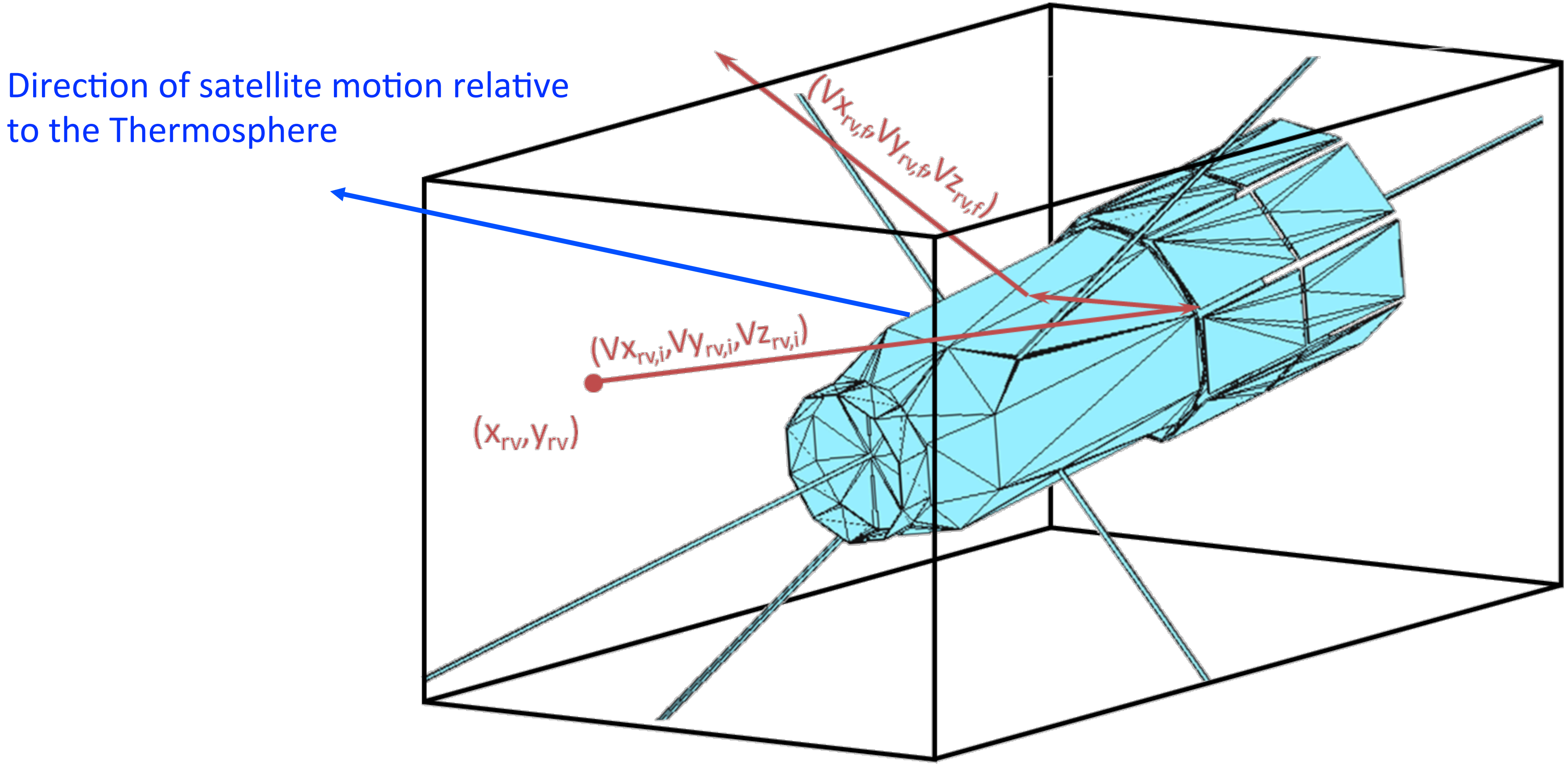
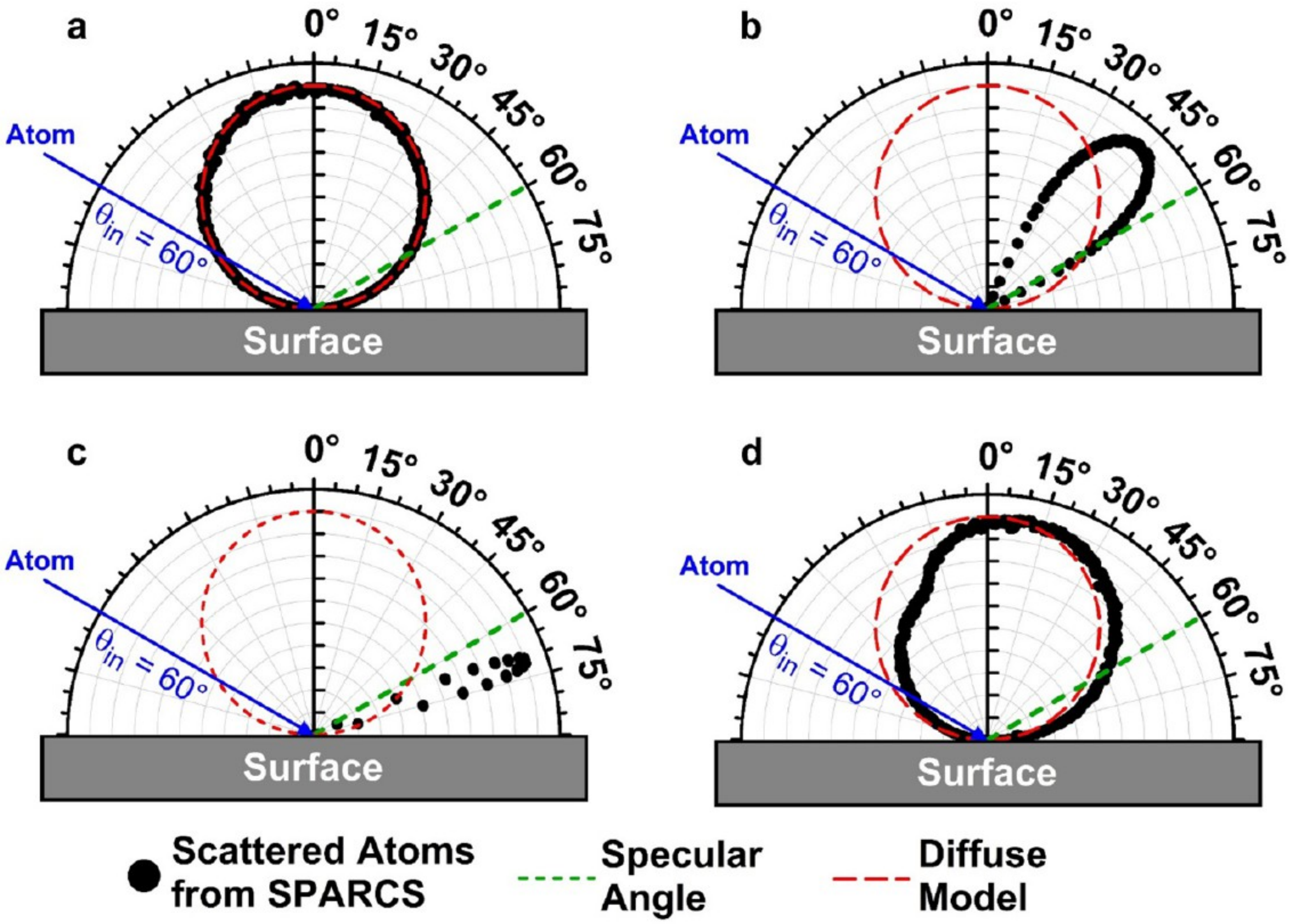
gas-surface interactions
(rarefied gas dynamics)
changes and uncertainty in orbital position

Computing Aerodynamic Forces



- Aerodynamics force is the sum of total molecular momentum change over a certain time
- Hotter flow can reach the side and back areas of satellites (the Thermosphere is hot)

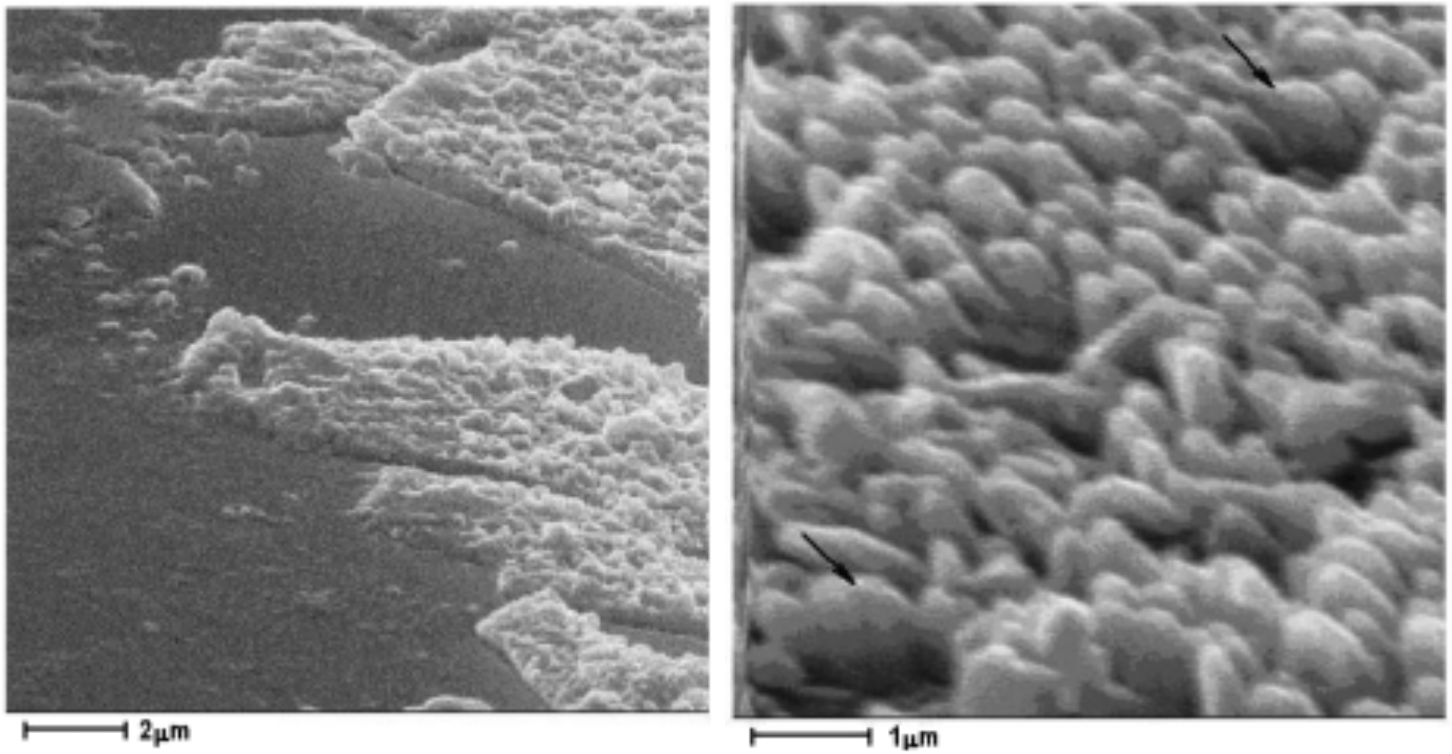
Gas-Surface Interactions



From Murray et al. 2017

Gas-Surface Interactions

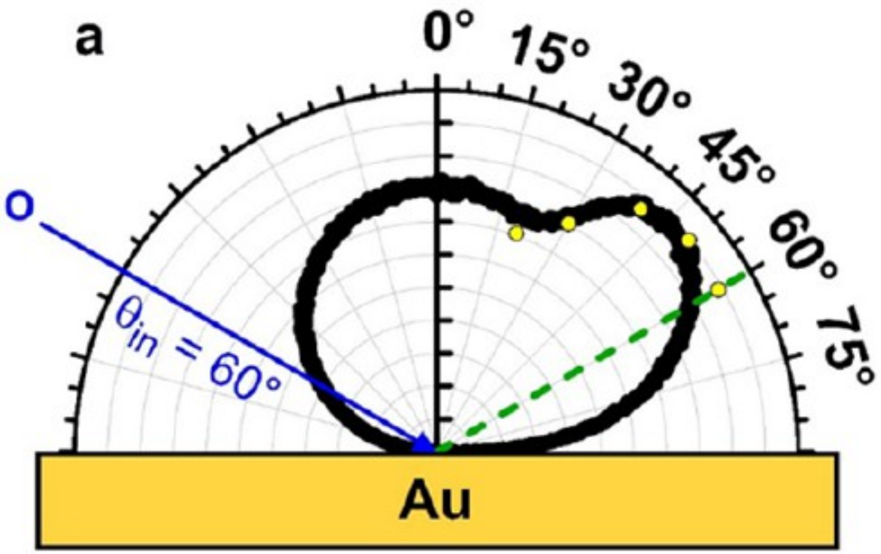
Skurat et al. 2011 (Journal of Spacecraft and Rockets)



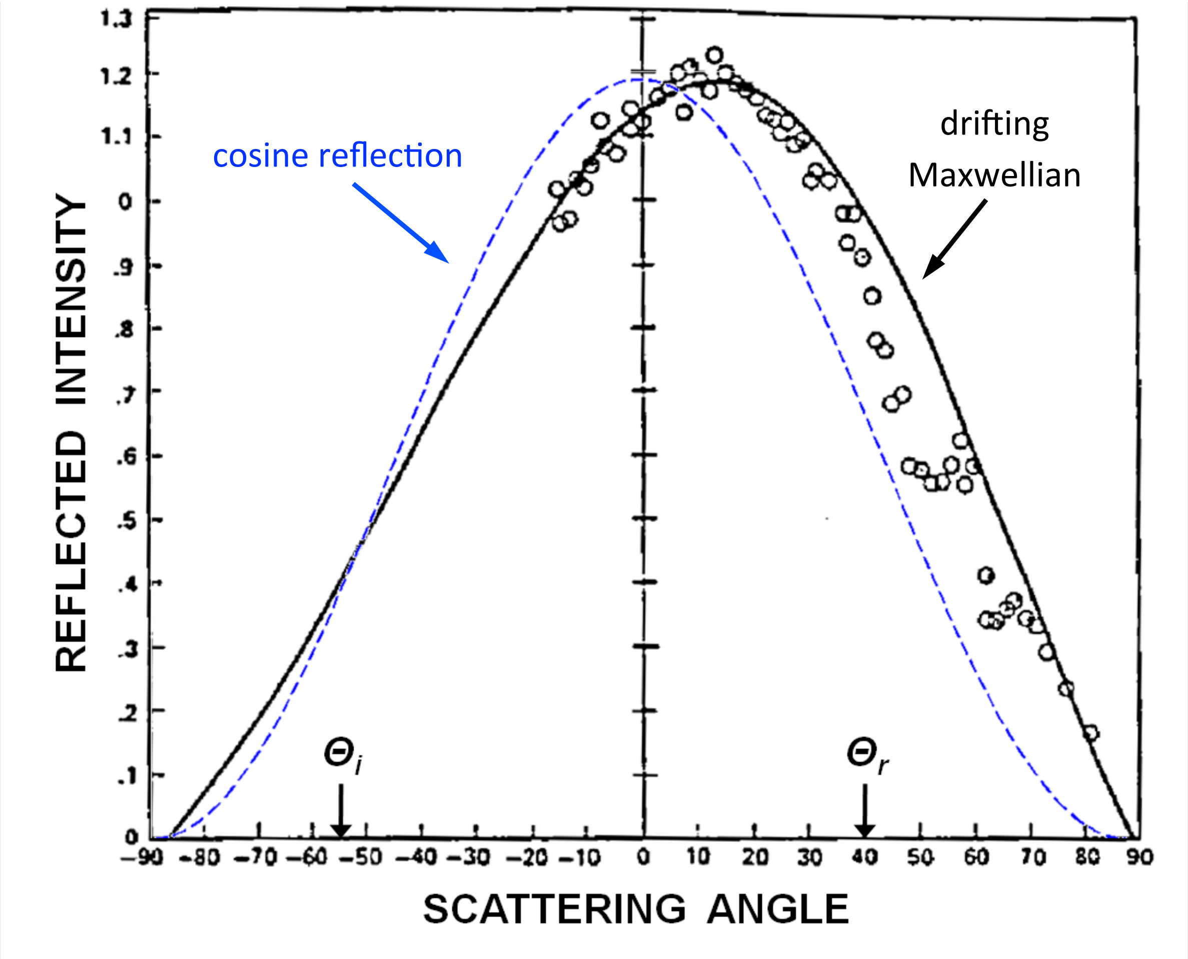
diameter of a strand of hair is ~100 μm,

length of N_2 molecule is ~0.0003 μm

Laboratory Experiments



Experience from Spacecraft Observations



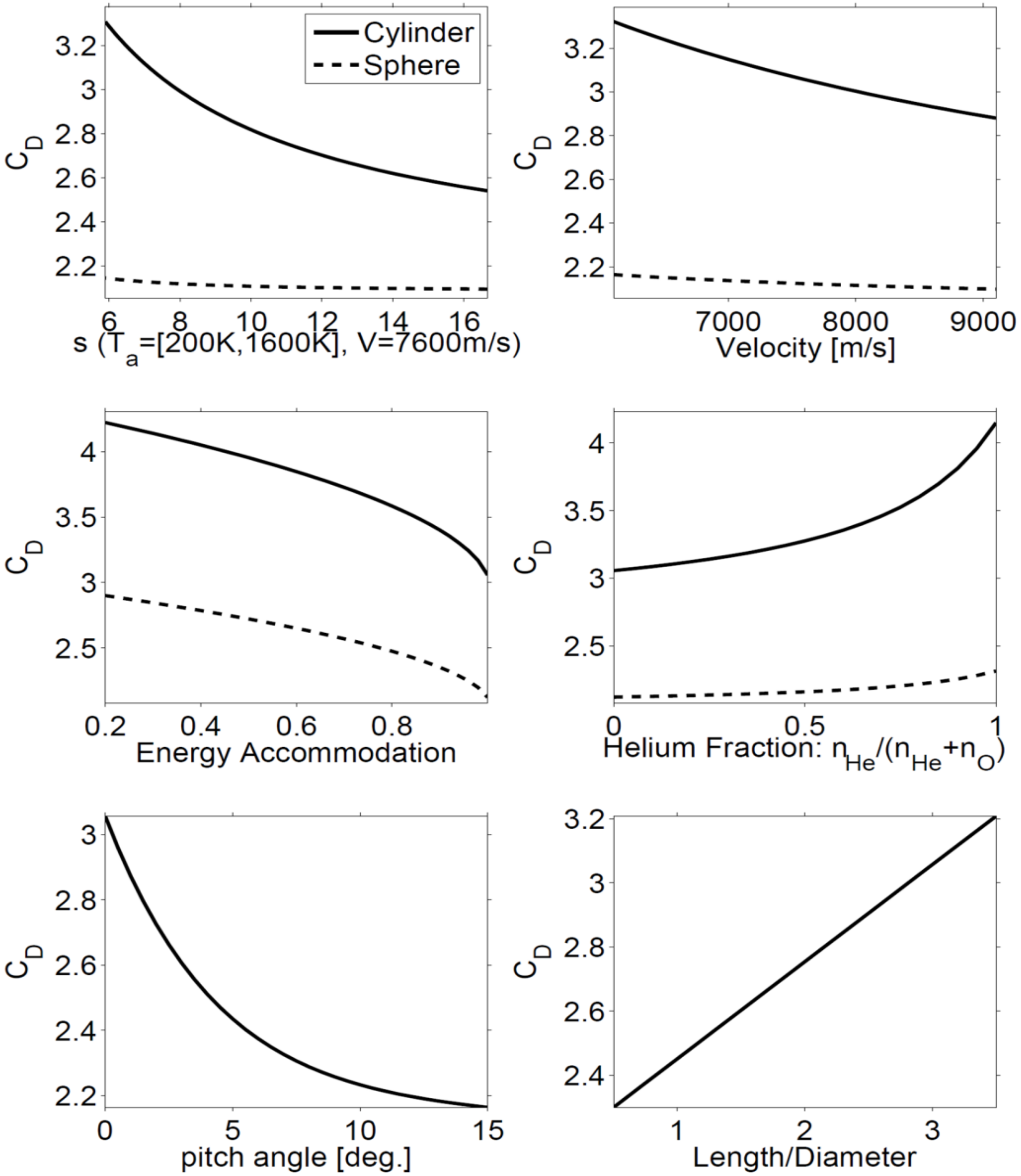
- Gregory and Peters found 98% reflect diffusely at shuttle altitudes and incident flow was completely accommodated [Gregory and Peters 1987]

Drag Coefficient Sensitivities

Thermal to bulk velocity ratio

Energy exchange with surface (Energy-Accommodation)

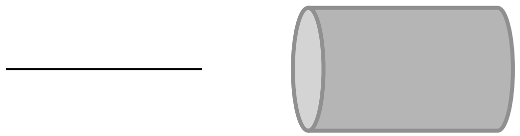
Attitude



Spacecraft velocity

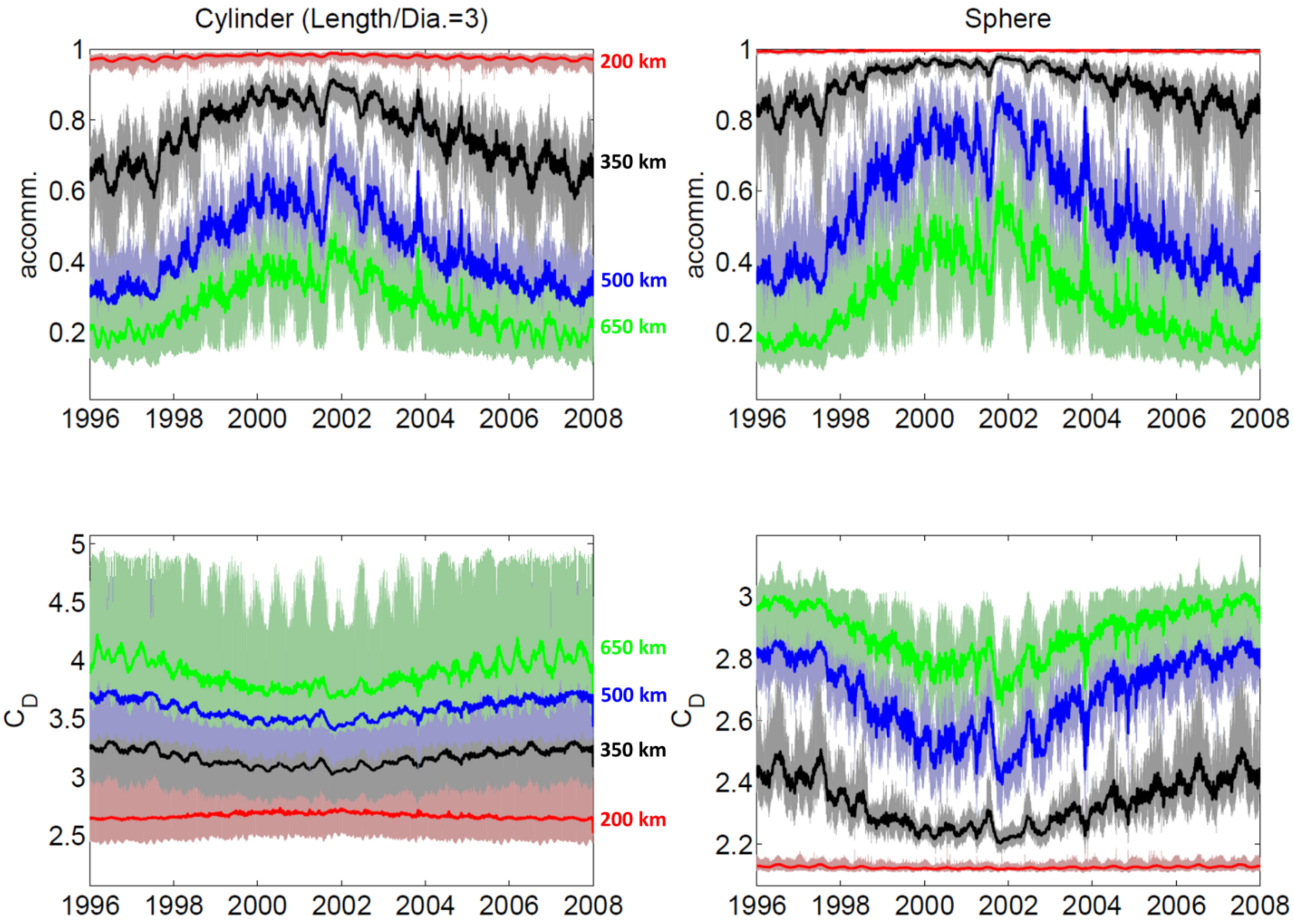
Composition

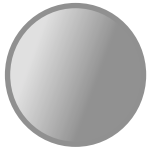
Shape



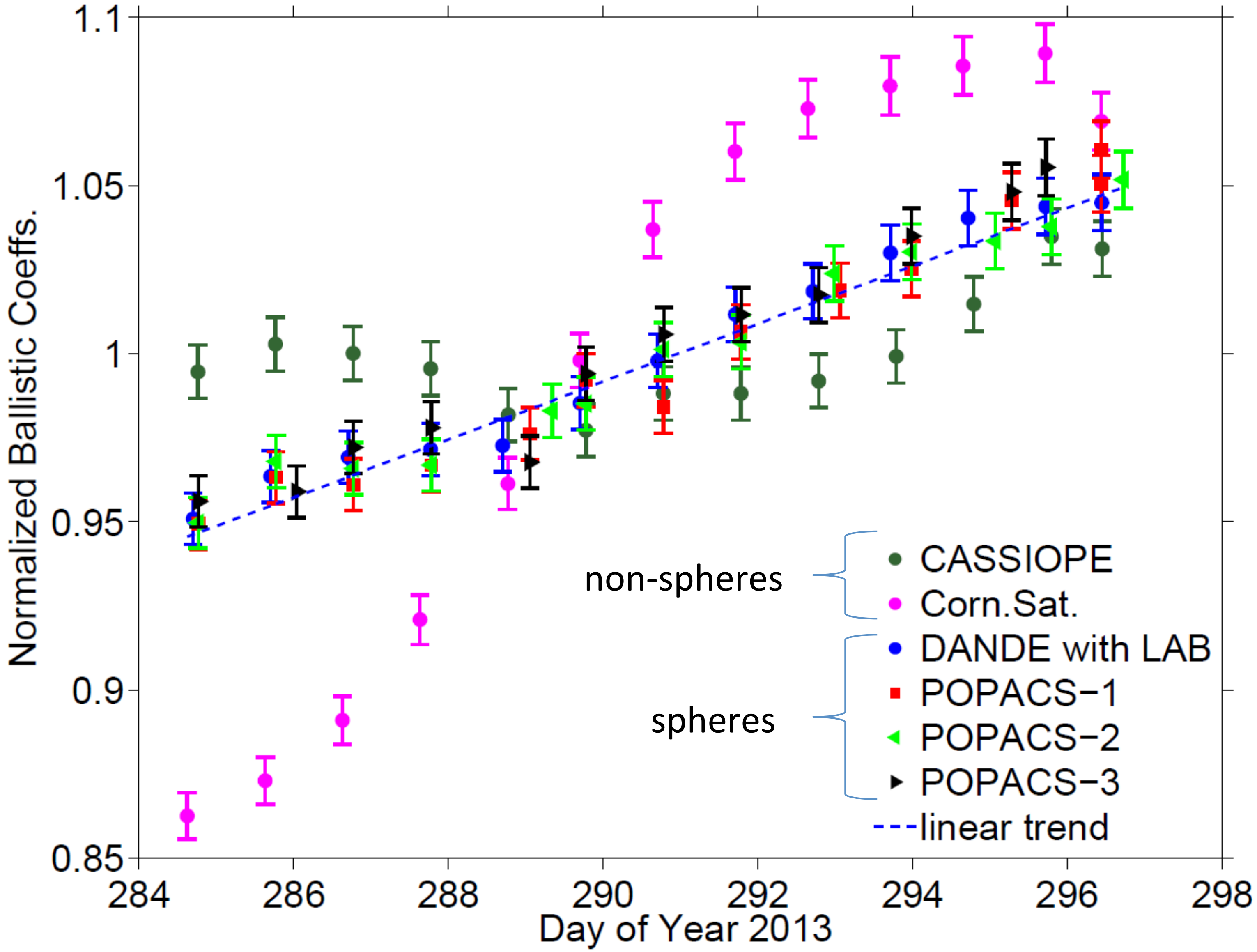
Cylinder of length to diameter ratio of 3 unless otherwise stated

Drag Coefficient Sensitivities

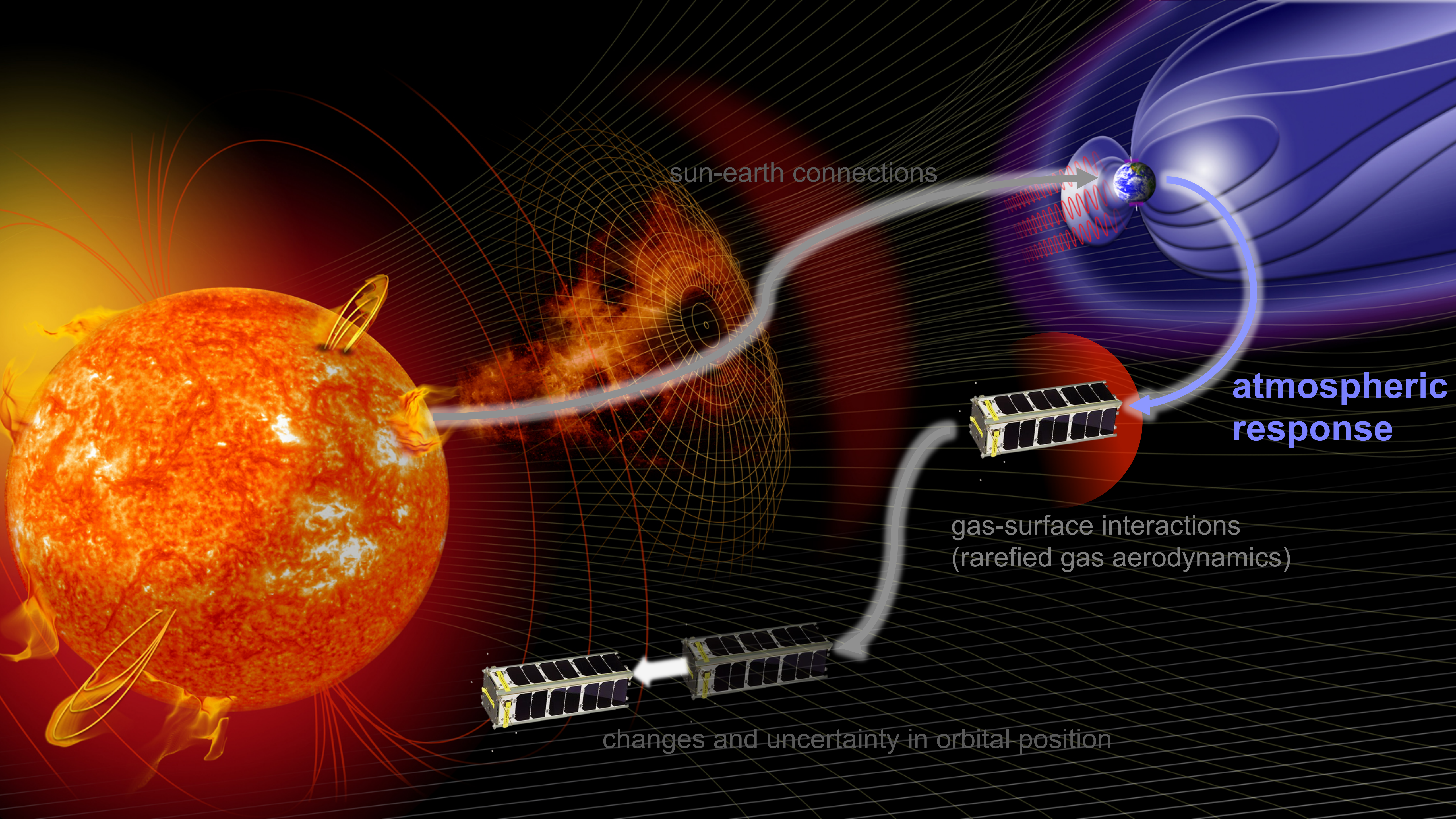




Cross-Sectional Area Variability



- Six satellites flying in close formation
- Decrease in density with time causes a secular trend in the fitted ballistic coefficient
- Spherical objects cluster around the secular trend
- Non-spherical objects change their cross sectional areas and exhibit significant ballistic variability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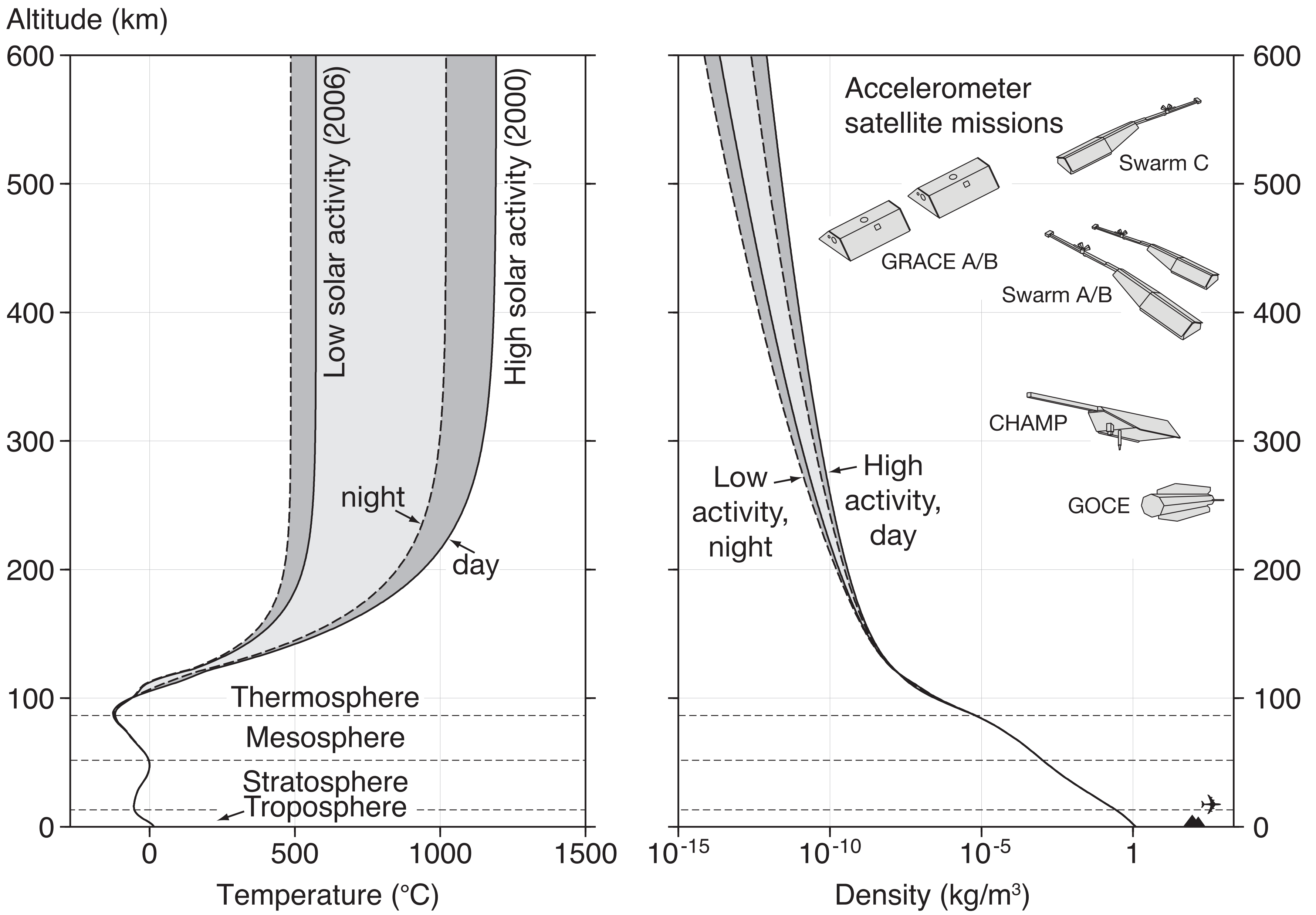
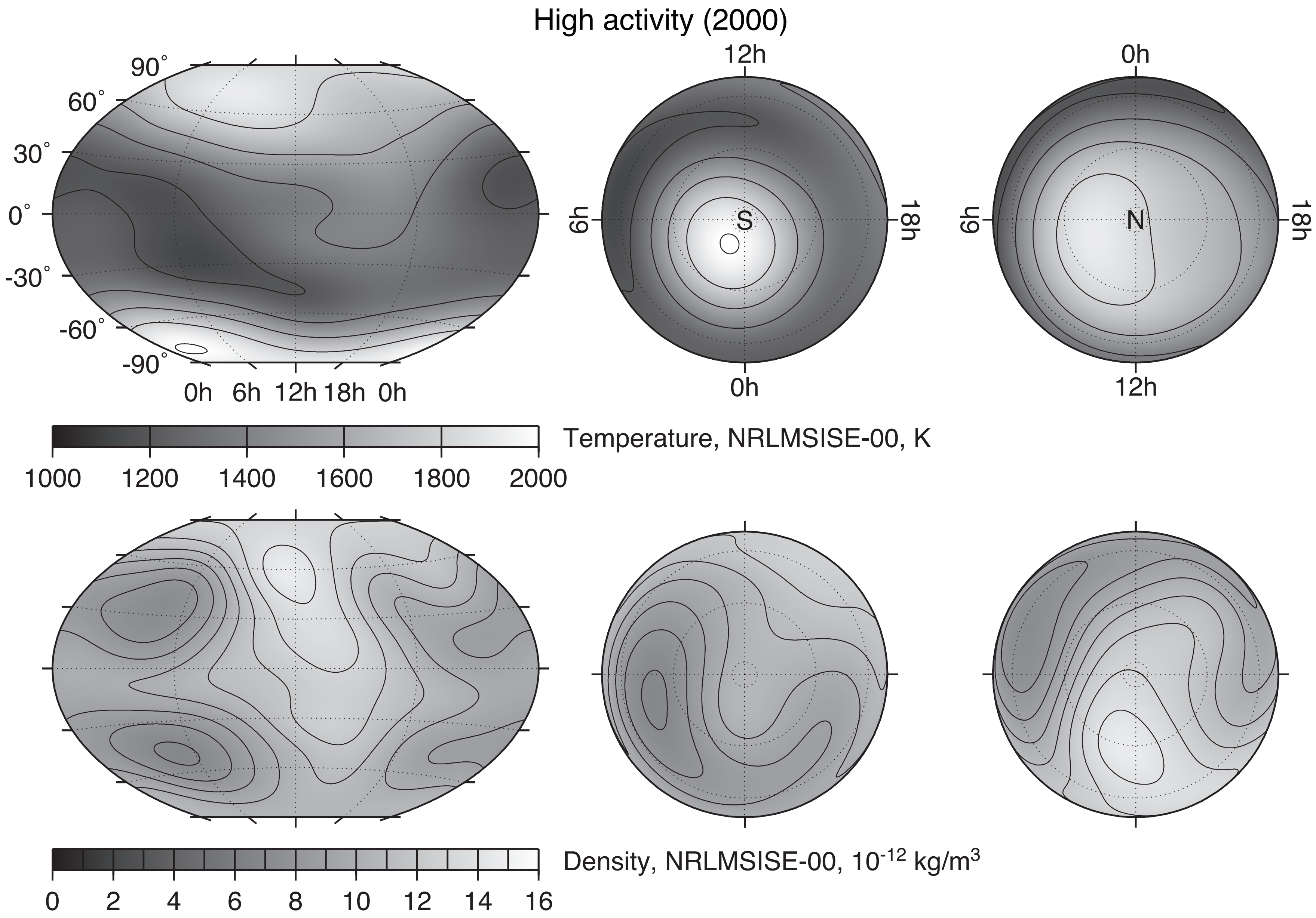
Atmospheric Densities



From Doornbos 2011

Atmospheric Densities (from and empirical model)



From Doornbos 2011

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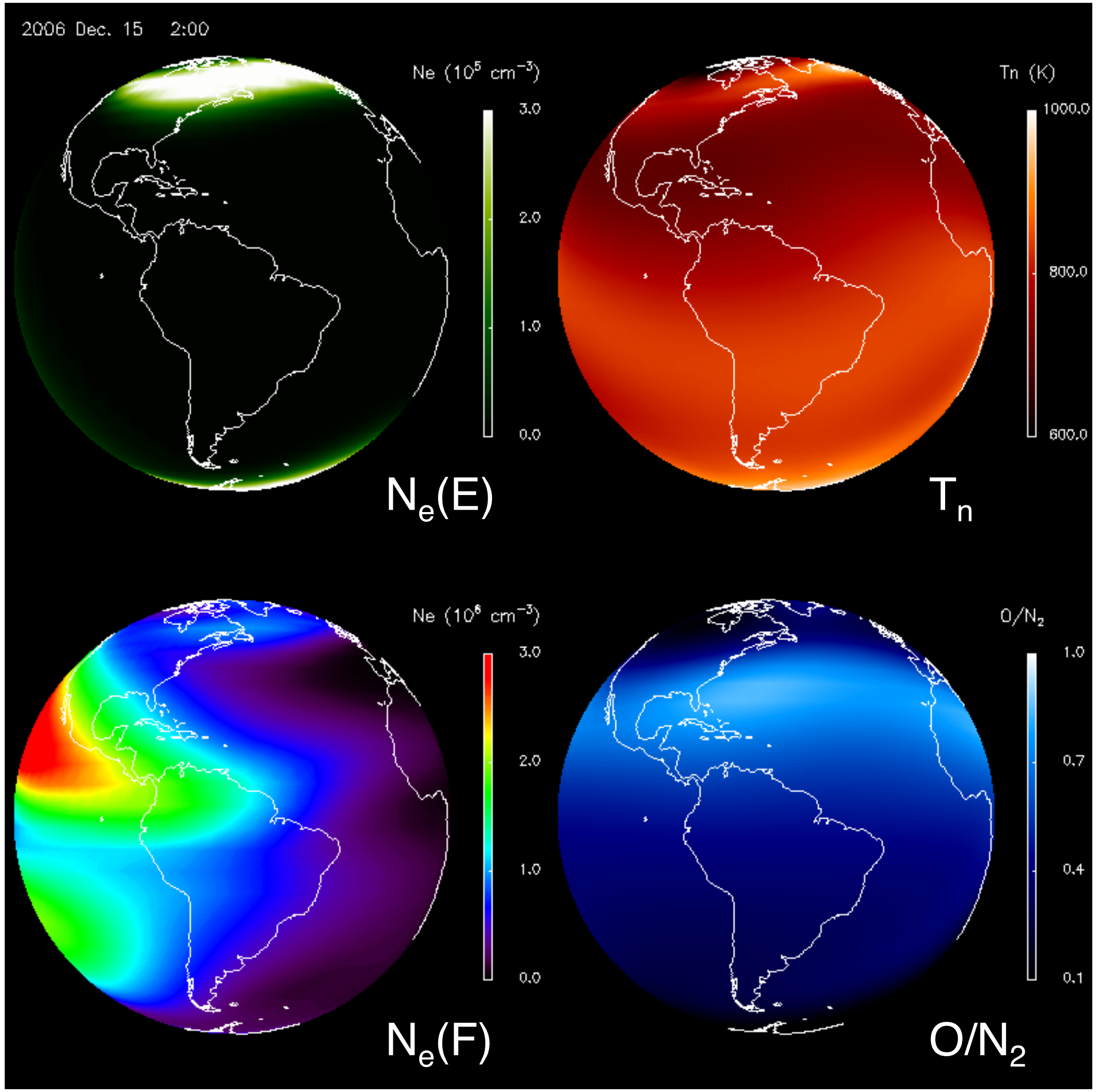
Global Circulation Models: Example



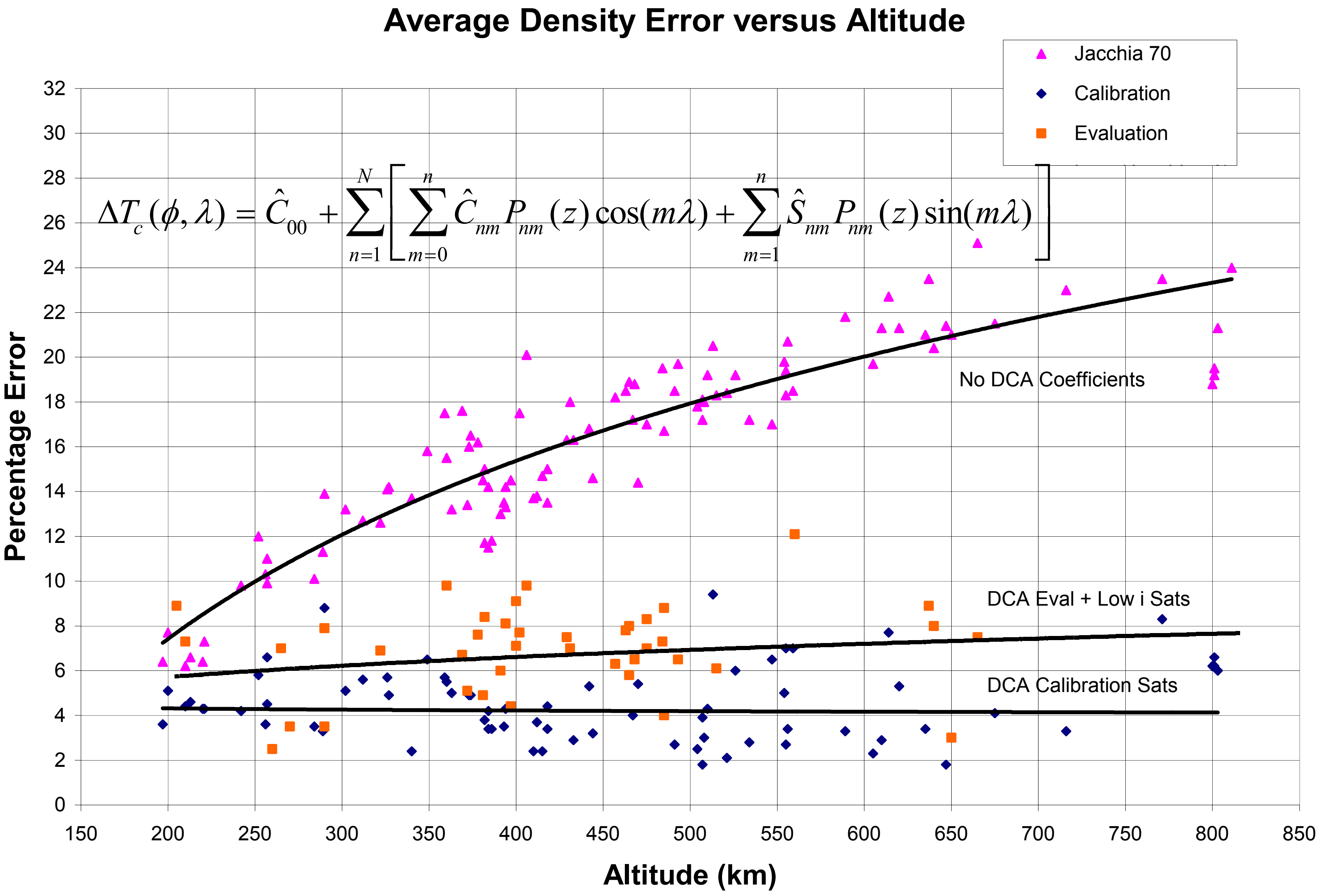
- Coupled momentum and continuity equations
- Runs-on-request at CCMC
- More information at: http://www.hao.ucar.edu/modeling/tgcm

- Other GCM's include
  - GITM
  - TIME-GCM
  - CTIPe
  - WAM
  - WACCM
  - …

Thermospheric Data Assimilation

Combining data and thermospheric models, and satellite aerodynamics we can constrain the satellite drag problem

High Accuracy Satellite Drag Model (HASDM)

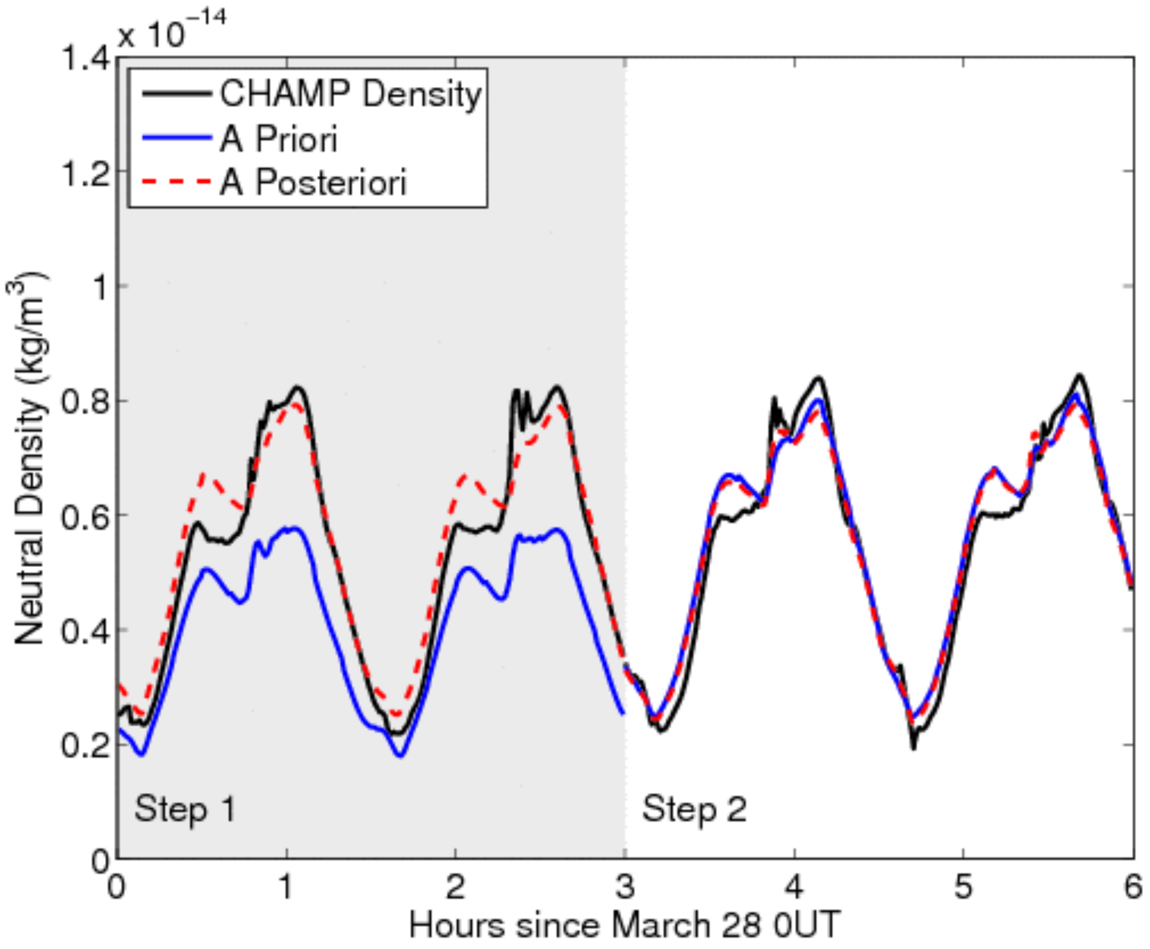


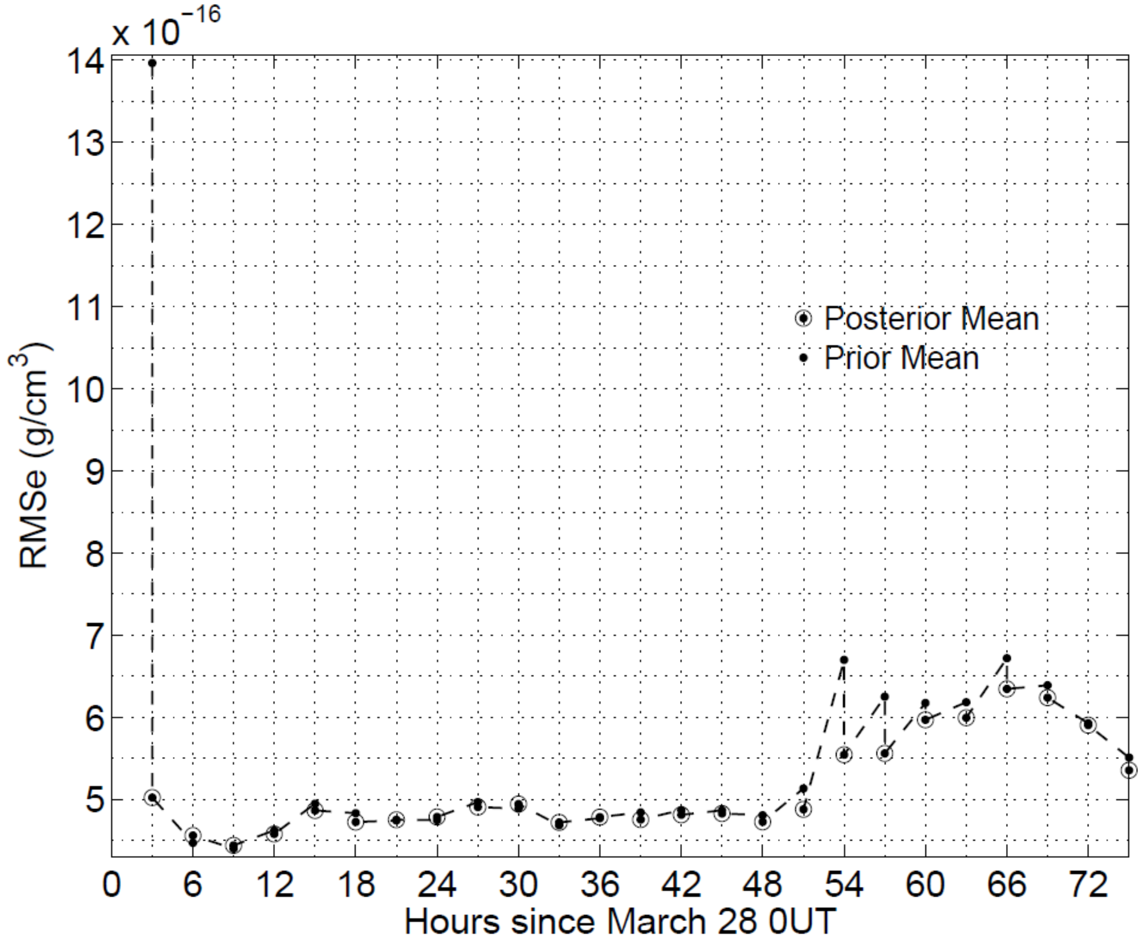
$$\Delta T_c(\phi,\lambda) = \hat{C}_{00} + \sum_{n=1}^{N}\left[\sum_{m=0}^{n}\hat{C}_{nm}P_{nm}(z)\cos(m\lambda) + \sum_{m=1}^{n}\hat{S}_{nm}P_{nm}(z)\sin(m\lambda)\right]$$

- Atmospheric temperatures in a 4x4 spherical harmonic expansion at two altitudes are included in the orbital fitting process for a set of ~70 calibration satellites
- Uses orbit or daily average satellite tracking data from AF radars
- Jacchia-type empirical model used as background for the assimilation

Bowman and Storz 2003

Iterative Re-Initialization, Driver Estimation & Assimilation (IRIDEA)





- Assimilation using accelerometer data and TIE-GCM model
- Uses very small ensembles
- For more (and more up to date) information see **Sutton 2018**

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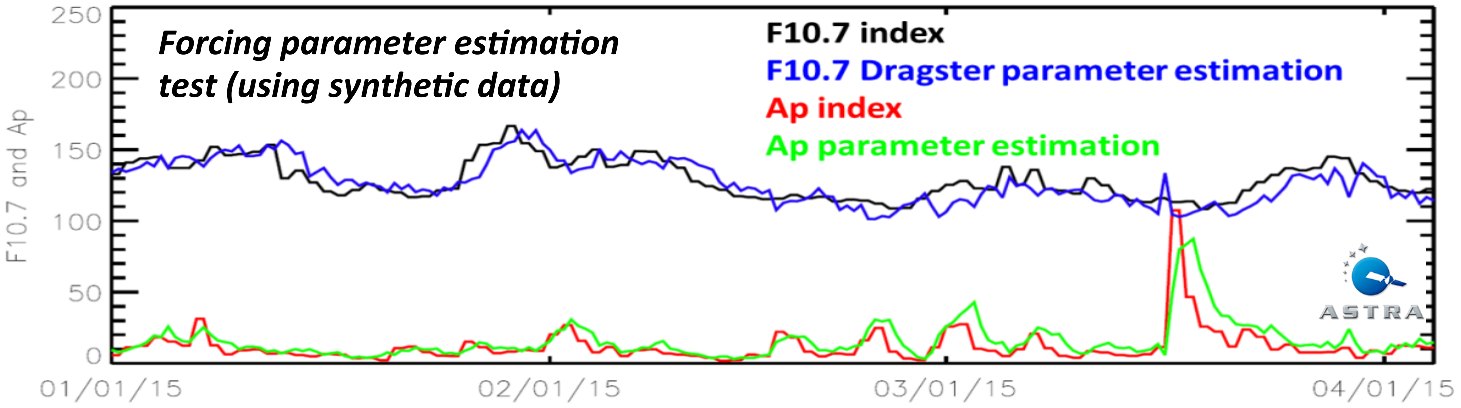
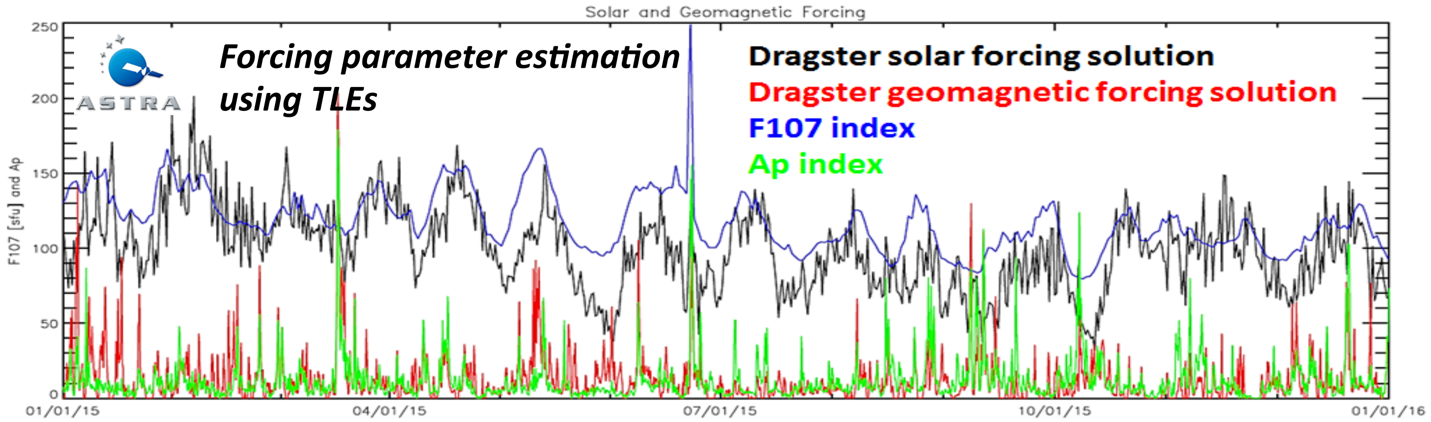
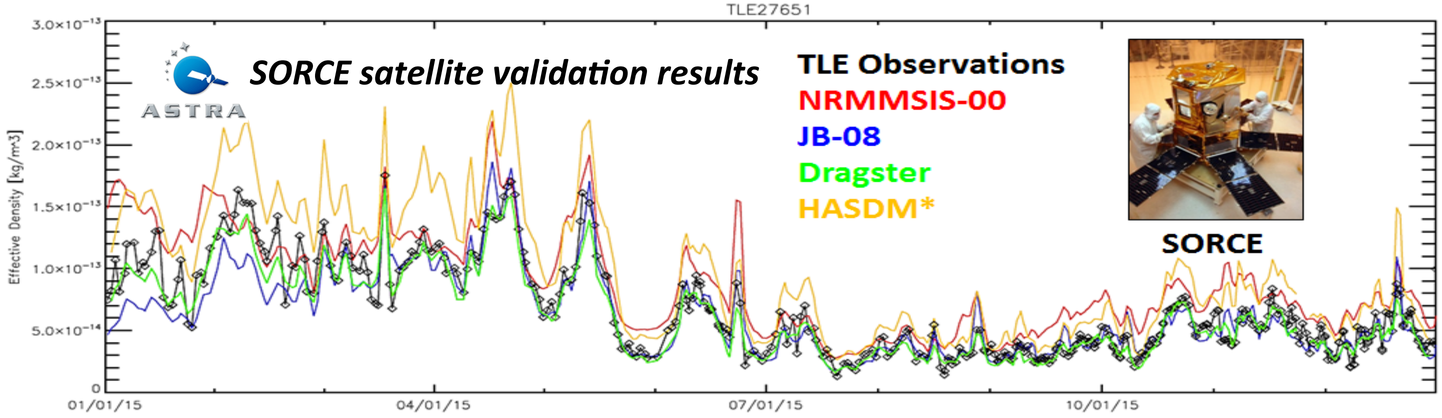
Dragster ENKF-based Technique







- Developed by ASTRA LLC. as part of AF funded STTR (CU is the educational partner)
- Uses 70-90 assimilation objects and processes satellites with variable ballistic coefficients
- Uses 30-90 ensemble members of NRLMSISE-00, TIE-GCM, and other models
- Estimates forcing
- Also estimates density corrections on a global grid at several altitudes
- Results shown assimilated TLE data (courtesy of ASTRA LLC.)
- For more information see **Pilinski et al. 2016 (AMOS technical paper)**

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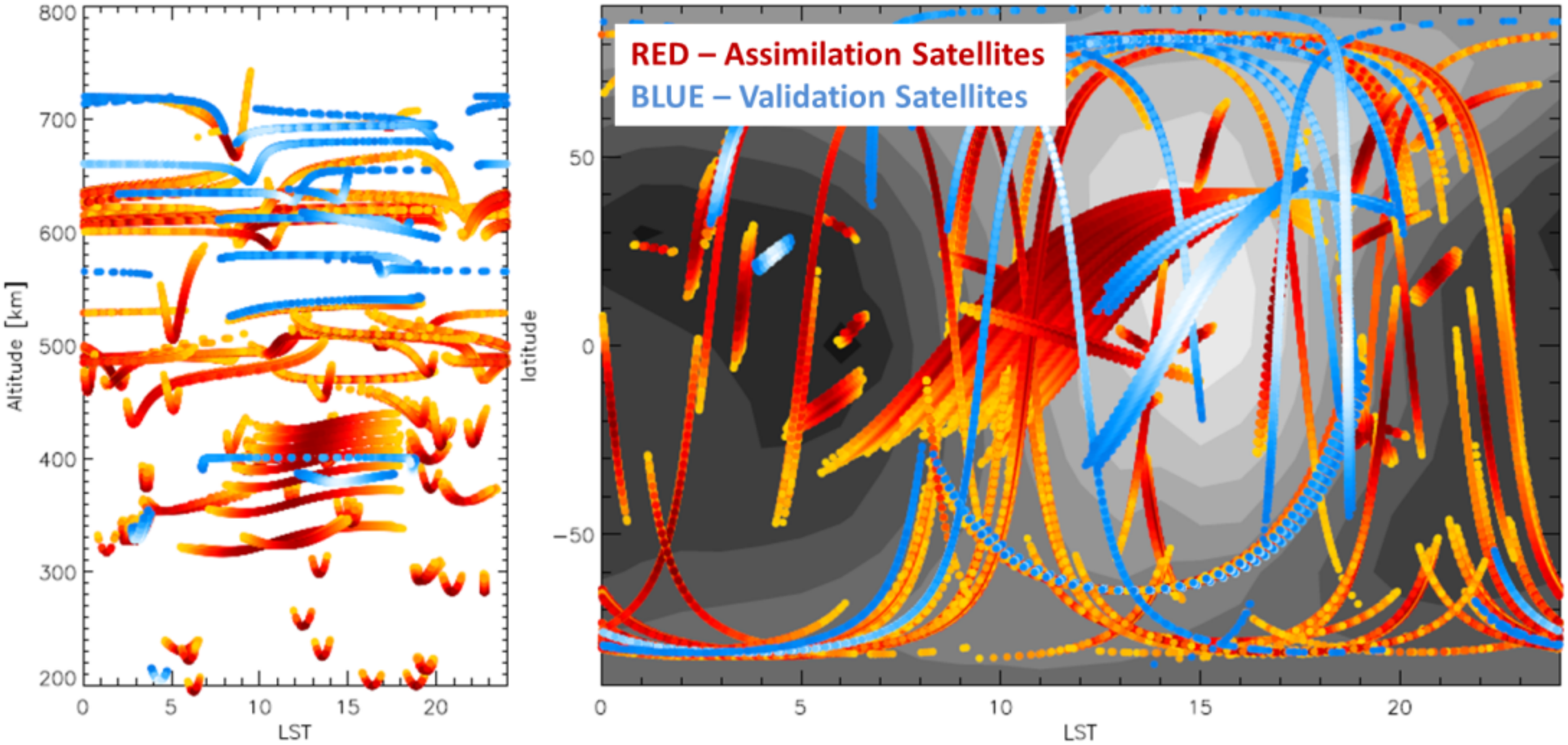
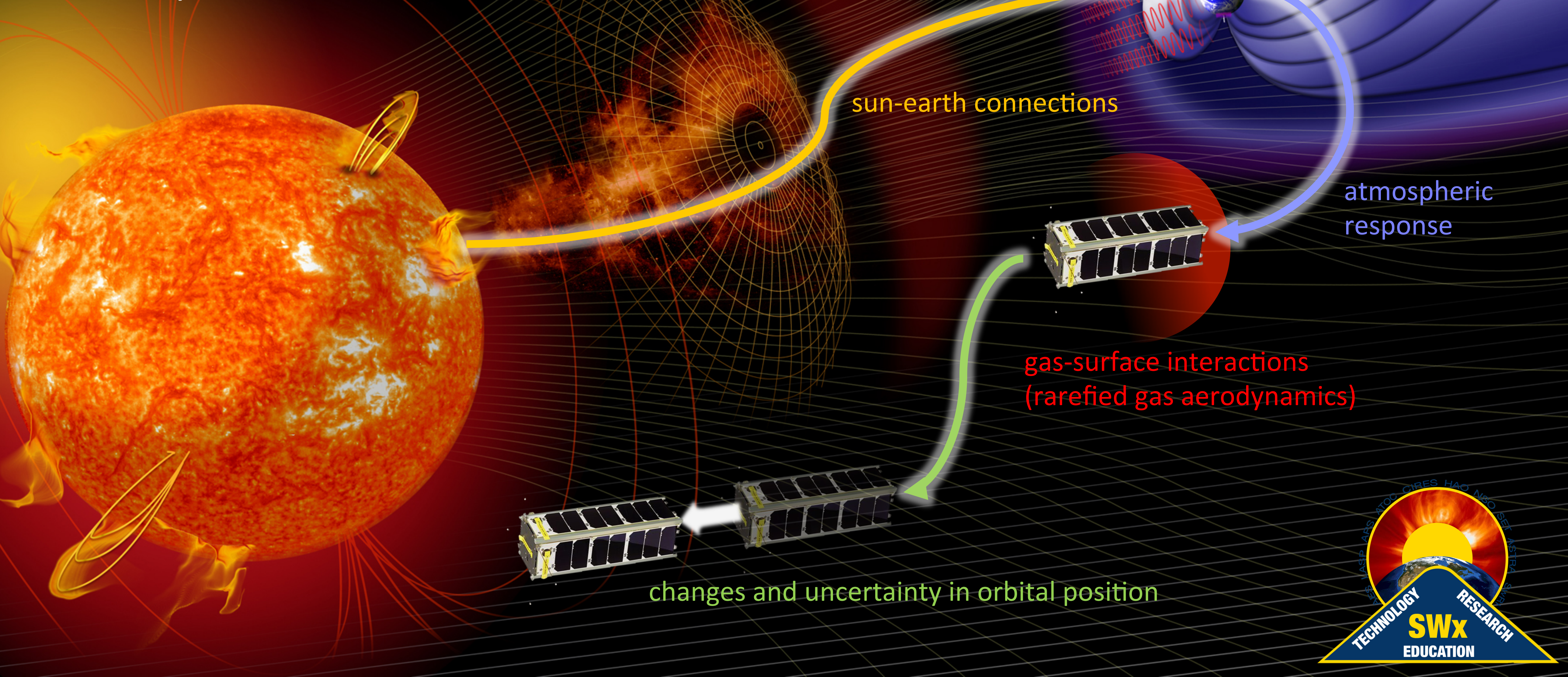
Assimilating Satellite Drag Data

Locations of 90% EDR for a set of assimilation and validation satellites

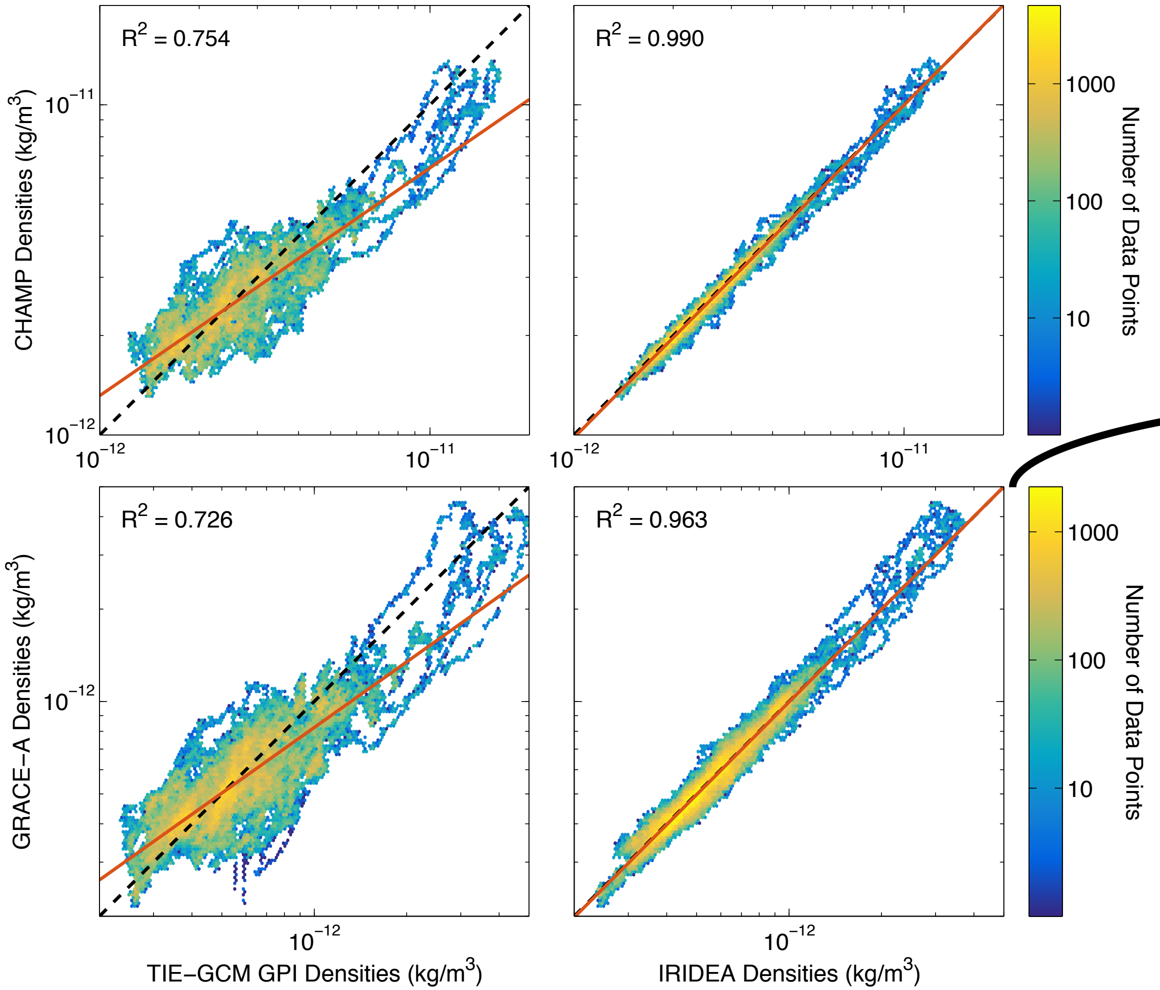


- Example from Dragster assimilation locations and density field at 400 km
- All drag is localized to some extent

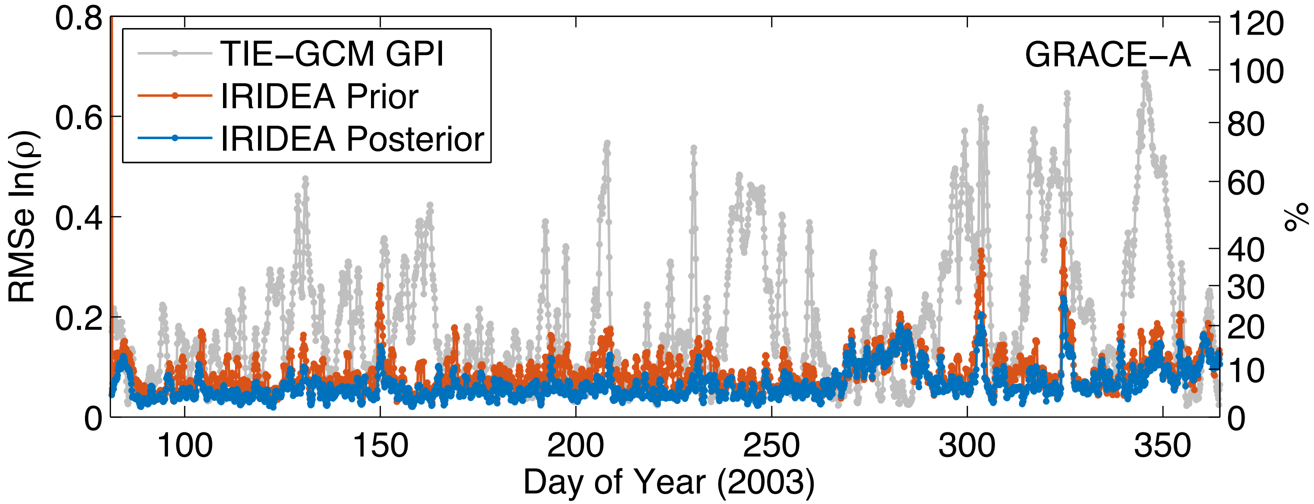
- Addressing satellite drag requires a multidisciplinary and multifaceted approach
- Astrodynamics + Aerodynamics + Heliophysics
- Observations + Models (Data Assimilation/Fusion)
- Industry, Government, Academia



IRIDEA: Backup Slides



GRACE Orbit-Averaged Validation results



[**Sutton 2018**] Histograms comparing orbit-averaged CHAMP (top) and GRACE-A (bottom) data with TIE-GCM (left) and IRIDEA (right) model output. An orbital running average has been applied to both data and model output prior to binning while the the original output can be seen in Figure S5 of the supporting information. Note: IRIDEA has only ingested the CHAMP data, while the GRACE-A data shown in the bottom plots are used strictly as an independent validation source.

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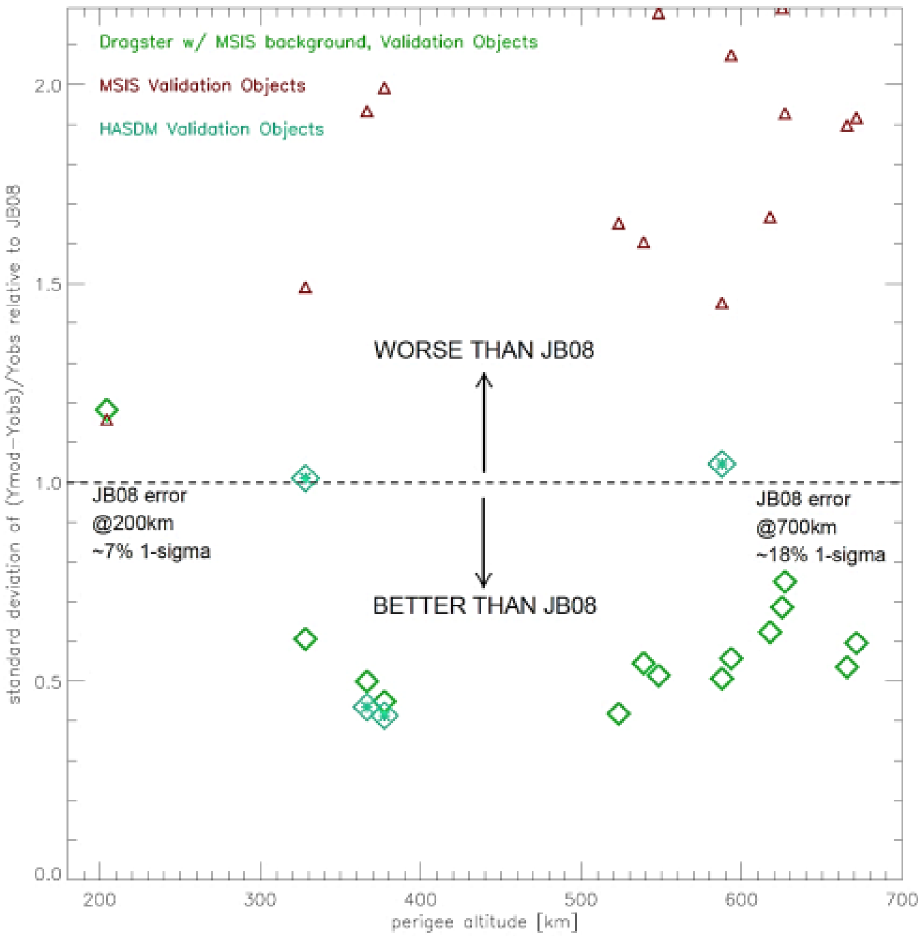
Backup Slides



Standard deviation errors for all validation objects relative to JB08 standard deviations. Values above the dotted line indicate performance worse than JB08 while values below the dotted line indicate performance better than JB08.

2015 validation metrics for select satellites.

Satellite *NORAD ID* *Name* *(Altitude)*	Model[2]	Standard Deviation	Bias	Prediction Efficiency
#27651 SORCE (591 km)	M	28%	32%	0.27
	J	20%	-7%	0.53
	H	25%	41%	0.06
	D	15%	-7%	0.68
#40314 Spinsat (390 km)	M	18%	15%	0.30
	J	11%	-12%	0.39
	H	11%	17%	0.33
	D	8%	-11%	0.46
#39267 DANDE (338 km)	M	24%	38%	0.31
	J	14%	10%	0.72
	H	17%	42%	0.10
	D	10%	2%	0.82
#27391 GRACE-A (393 km)	M	19%	31%	-0.08
	J	11%	-0%	0.63
	H	9%	33%	-0.15
	D	7%	0%	0.76

[2] M-MSIS J-JB08 H-HASDM D-Dragster